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COST AND EMISSION STUDIES OF A HEAT ENGINE/BATTERY HYBRID FAMILY CAR

TRW Systems Group

Prepared for:

Environmental Protection Agency

April 1972

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COST AND EMISSION STUDIES OF A HEAT ENGINE/BATTERY HYBRID FAMILY CAR

G.H. Gelb
B. Berman
E. Koutsoukos

Prepared for

Division of Advanced Automotive Power Systems Development
Office of Air Programs
Environmental Protection Agency

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An experimental and analytical study was conducted. The broad objectives of the studies were as follows: to select and analyze the performance of series and parallel configured heat engine/battery hybrid family cars; to define the relative efficiencies, weight and costs of hybrid power trains; to generate data characteristics of selected three-component catalysts; to perform preliminary materials screening and development of a hydrocarbon emission trap (hydrocarbon accumulator); and to demonstrate that a hybrid car with an internal combustion engine could meet the 1975/76 emission goals. This document describes the work done and presents the results and conclusions.

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Details of illustrations in
this document may be better
studied on microfiche.

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FOREWARD

This report presents the results of analytical and experimental work performed during the period from July 1971 through February 1972 under contract number 68-04-0058 for the Environmental Protection Agency. The overall program direction and report preparation was the responsibility of Dr. George H. Gelb of Power Conversion and Applications, Advanced Technology Division, TRW Systems Group. Mr. Baruch Berman of the same organization led the analytical studies of the electrical systems of the hybrid power train. He was assisted by Dr. T.C. Wang in the power train modeling phases and Mrs. Roselyn Lipkis who performed the computer programming and simulations. Dr. Elias Koutsoukos of the Chemical Engineering Department of the Applied Technology Division supervised the emission-related experimental portions of the program.

The authors would also like to express thanks to Mr. Harry Gehm who aided in instrument engineering and engine modifications and Messrs Ernie Hoover and Thomas Hurst for their technical support in the laboratory activities.

Dr. Jalal Salihi managed the project for the Division of Advanced Automotive Power Systems Development, Office of Air Programs, Environmental Protection Agency. Dr. Salihi was assisted by Mr. Edward Beyma and Dr. Joseph Sommers of the Office of Air Programs.

NOMENCLATURE

a_R - vehicle acceleration, mph/sec

g_1 - gear ratio at gear 1 (differential)

g_2 - gear ratio at gear 2

I_A - alternator current, amps

I_B - battery current, amps

I_M - motor current, amps

I_{PCU} - PCU current, amps (series configuration)

I_{PCUA} - alternator PCU current, amps (parallel configuration)

I_{PCUM} - motor PCU current, amps (parallel configuration)

P_{Ai} - power into alternator, watts

P_{Ao} - power out of alternator, watts

P_B - battery power, watts

P_{ij} - probability of occurrence of the i^{th} velocity with the y^{th} acceleration in the LA-4 matrix

P_{IC} - power out of engine, watts

PCU - power control unit

P_{Mi} - power into motor, watts

P_{Mo} - power out of motor, watts or hp

P_0 - power transmitted out of planetary gear to propeller shaft, hp

P_{PCU} - PCU power, watts (series configuration)

P_{PCUA} - alternator PCU power, watts (parallel configuration)

P_{PCUM} - motor PCU power, watts (parallel configuration)

P_R - vehicle road power requirement, hp

r - driving wheel radius, 1 foot

R_B - battery resistance, ohms

V_A - alternator voltage, volts

V_B - battery voltage, volts

V_{Bi} - battery open circuit voltage, volts

V_M - motor terminal voltage, volts

V_R - vehicle velocity, mph

ω_M - motor speed, rpm

ω_R - road velocity, rpm

α - chopper duty cycle, defined as the ratio of time that the power silicon controlled rectifier is conducting to the total period of the chopper

ΔP_{PCUA} - alternator PCU power loss, watts

η_A - alternator efficiency

η_{g0} - planetary gear efficiency

η_{g1} - gear 1 efficiency

η_{g2} - gear 2 efficiency

η_{gM} - variable gear efficiency

η_M - motor efficiency

η_{PCU} - PCU efficiency (series configuration)

η_{PCUA} - alternator PCU efficiency (parallel configuration)

η_{PCUM} - motor PCU efficiency (parallel configuration)

η_{RE} - rectifier efficiency

η_S - overall efficiency from engine to rectifier

η_{SYS} - overall efficiency for entire configuration

τ_M - motor torque, ft-lb

τ_R - road torque, ft-lb

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ABSTRACT

TRW Systems has conducted a combined analytical and experimental study, "Cost and Emission Studies of a Heat Engine/Battery Hybrid Family Car," for the Division of Advanced Automotive Power Systems Development, Office of Air Programs, Environmental Protection Agency under contract number 68-04-0058.

The broad objectives of the studies were to:

- Select and analyze the performance of series and parallel configured heat engine/battery hybrid family cars.
- Define the relative efficiencies, weight and costs of hybrid power trains.
- Generate data characteristics of selected three-component catalysts.
- Perform preliminary materials screening and development of a hydrocarbon emission trap (hydrocarbon accumulator).
- Demonstrate that a hybrid car with an internal combustion engine could meet the 1975/76 emission goals.

Analytical Studies of Heat Engine/Battery Hybrid Power Trains

Selection of a candidate series system for analysis was made on the basis of; ability to meet the EPA vehicle design goals, total system weight and volume, overall efficiency at selected speeds and accelerations and preliminary cost appraisals. From a field of several series systems, one system, the full voltage series hybrid was selected. The parallel system selected for analysis was that using the Electromechanical Transmission (EMT) developed by TRW Systems.

Extensive computer modeling of both systems was performed. Detailed mathematical models of alternators, traction motors, power control units (PCUs), gearing and batteries were developed by a combined approach of analysis and utilization of equipment manufacturers' data. Computations were made to determine the performance of each of the major subsystems in terms of power level, current, voltage, speed, torque and efficiency for a matrix of vehicle velocity-acceleration points. The matrix was broad enough to cover the complete velocity range of vehicle operation at all reasonable acceleration and deceleration rates.

The matrix performance quantities and their probability of occurrence in the LA-4 driving mission were combined to establish the average and RMS values for a realistic driving cycle. Engine powers, battery impedances, gear efficiencies and operation without regeneration and transmission gear ratios were adjusted to develop sensitivity trends of system performance to these variables. The effectiveness of regenerative braking was investigated.

In the absence of any accessory loads, the efficiency of the parallel system between the engine output shaft and the driving wheels could be as high as 77%. (All overall efficiency values are based on maintaining the battery's impedance increases and gearing losses increase, system efficiency may fall to about 68%. With a steady accessory load of 5 horsepower, the engine shaft output must increase and the engine-to-wheel efficiency would fall to 54.3% and 49.8%, respectively.

The series hybrid system exhibits a somewhat lower efficiency on the LA-4 cycle. Without accessory load but with an advanced battery and low loss gearing its efficiency is near 55%. As battery and gearing degrade, system efficiency may fall closer to 48%. If the 5 horsepower accessory load is added, these values will decrease to 43.3% and 38.8%, respectively. Since the series system's generator and traction motor must be rated for continuous power at top vehicle speed, larger machines are required. On the other hand, the series system offers a greater flexibility of operation--full engine output can be utilized at any road speed.

Multiple gear ratios between the traction motor and rear wheels was shown to be important to the overall system efficiency. Its impact was slightly greater in the parallel system (about 8 percentage points) since the traction motor's torque rating is lower than that of the series system and without step down gearing, the RMS current placed a heavier burden on the machines.

Regenerative braking was shown to improve the overall efficiency in both systems. In the series system, regenerative braking improved the system efficiency by approximately 10%. The parallel system, the EMT, uses the traction motor as a generator as part of its normal mode of driving wheel torque control and thus regenerative is inherent in the system. However, computations showed that utilizing the kinetic energy of the car for battery charge during decelerations could affect the system efficiency by a larger amount that in the series system.

Planetary gear efficiency was shown to dominate the overall system efficiency of the parallel system, with all other parameters held constant. A change in the planetary system's efficiency from 90 to 80% decreased the overall efficiency by 11%--almost equal in magnitude to the efficiency gain resulting from the use of a variable gear ratio.

It is important to note that these results are dependent on the detailed models which are chosen to represent the characteristics of the power trains components as well as the specific driving profiles over which the evaluations are made. Thus, while the results are arrived at using valid techniques of modeling and computations, the absolute values of efficiency, etc. should only be used in terms of trend and comparison.

The weight of the complete parallel system including engine, gearing and batteries is approximately 87-89% of the series system. The OEM cost of the series power train, excluding batteries and engine is nearly 25% higher than the parallel system; however, the impact on a comparison of both systems' total cost would be far less when the added costs of the engine and battery are factored in.

Estimates of the new car costs for hybrid vehicles are difficult to establish without a detailed knowledge of the OEM to consumer makeup structure. Rather than project a first cost based on arbitrary costs, models, cost comparison between hybrids and conventional cars was made on fuel consumption and battery replacement estimates. It is estimated that the fuel economy savings of hybrid operation can pay for battery replacement costs.

Experimental Studies of Emission Control of ICE/Battery Hybrid Power Trains

Steady state data on the conversion efficiency of a three-component catalyst was taken. The catalyst, composed of copper oxide on alumina, is manufactured by Harshaw Chemical Company and activated by TRW Systems. Initial tests were carried out on the exhaust flow from one cylinder of a VW 1600 cc engine. The test catalytic converter was sized for single cylinder exhaust flow rates ranging from 20,000 to 35,000 ft^3/ft^3 hour. Catalyst bed temperatures ranged from 1200 to near 1600°F.

The data exhibited characteristics which were expected on the bases of chemistry and selectivity of nitric oxide (NO) reduction. The NO conversion efficiency of the catalyst (defined as the ratio of the concentration of a specie at the converter outlet to the inlet concentration) was in excess of 90% for air-fuel ratios having a reductant to oxidant ratio in excess of one; that is, for all rich mixtures. The hydrocarbon (HC) and carbon monoxide (CO) efficiencies increased as the air-fuel ratio became leaner. At stoichiometry where the total reductants and oxidants were equal, the simultaneous conversion of all three pollutants was over 90%. Beyond stoichiometry, the NO conversion fell rapidly with the addition of excess oxygen. HC and CO conversions remained close to 100% with increased mixture leaness. The overall effect of low HC, CO conversion on the rich side of stoichiometry and low NO conversion on the lean side restricts the air-fuel range over which the catalyst can operate effectively. For example, the air-fuel ratio at 1390°F bed temperature must be maintained within ±0.2 of stoichiometry to insure the simultaneous conversion exceed 80%.

Space velocity appeared to play a smaller role on conversion than temperature--at least over the ranges investigated in these experiments. With increasing temperature the bed of effective catalyst performance broadens. In addition as the temperature is increased, the relative conversion efficiencies of HC and CO reverse--at low temperature, (~1200°F) CO conversion is favored, at higher temperatures (~1500°F), CO conversion is favored.

Various materials were screened as candidates for use in hydrocarbon accumulator. The materials included activated carbon and charcoal, silica gel, molecular sieve and alumina. Tests were conducted by exposing a constant volume of material to the exhaust of a single cylinder of the VW engine. The engine and accumulator were started cold; the mixture ratio and flow rates were controlled to produce as reproducible starting conditions as possible.

Tests indicated that activated carbons are the most efficient material for trapping hydrocarbons in the exhaust stream during cold starts. They have the highest mass capacity at any given temperature and are still able to adsorb hydrocarbons at nearly twice the temperature that its nearest competitor loses its adsorption capability.

In order of decreasing effectiveness were molecular sieve, silica gel and alumina. While the molecular sieves showed promise as a secondary choice Pittsburgh Activated Carbon of the BPL series was chosen for use in a full scale hydrocarbon accumulator. This material exhibited no chemical or physical deterioration after several adsorption-desorption cycles in which it was exposed to temperatures near 600^{o}F and space velocities greater than 80,000 V/V/Hr.

A 1971 Chevrolet Vega engine was selected for use in full scale system emission tests. The engine was modified for hybrid operation; the major modification was replacement of the carburetor with an intake manifold fuel injection system adapted from the VW fuel injection equipment.

A test converter containing approximately 400 cubic inches of the TRW-Harshaw catalyst was constructed to treat the total exhaust of the Vega. Tests were run to characterize the steady state conversion and the production of ammonia. The conversion efficiencies of this converter were similar to the single cylinder data; however, better geometry caused the bed to operate at higher temperatures than the single cylinder tests at equal space velocities.

The composition of the exhaust of the engine showed that on the rich side of stoichiometry, sizable corrections of the reductant-oxidant ratio had to be made to account for hydrogen. Measurements of ammonia produced in the catalyst indicated that the ammonia concentration at rich mixtures (about 2 points from stoichiometry) could be almost 50% of the NO concentrations. However, at stoichiometry, the ammonia was only 1% of the NO concentration. Ammonia production at a given air-fuel ratio increased as the catalyst bed temperature decreased--a result predicted by thermodynamics.

Two catalytic converters supplied by Universal Oil Products (UOP) were tested on the Vega. These devices, containing a light loading of platinum on alumina were operated at similar exhaust velocities as in the TRW-Harshaw characterization tests. The converters had good HC and CO oxidation properties for lean mixture ratios; however, the peak NO conversions were much less than that exhibited by the copper oxide catalyst.

The hydrocarbon accumulator and full scale TRW-Harshaw catalytic converter were combined with the Vega-EMT power train. Emission measurements of the hybrid system were made according to the latest Federal procedures--i.e., cold start transient bag, stabilized hot bag and hot start transient bag. Chemiluminescent measurement of NO_x was used. The engine was run on a power schedule which simulated operation on the Federal driving cycle.

The 1975-76 emission standards were achieved in several tests. The hydrocarbon accumulator was shown to have a dramatic impact in total HC emissions. The catalytic converter was able to light off rapidly and control NO emissions well enough to provide a margin of NO_x control under the 1976 standards. CO was found to be the most difficult specie to control. CO problems were directly attributable to cold start emissions during the period when considerable engine choking was required.

Physical changes in the catalyst were small, if any, over the testing period which amounted to approximately 100 hours. The most noticeable change appeared to be a decrease in the total bed volume; however, this may have been do to the bed being shaken on the test stand and settling.

SUMMARY AND CONCLUSIONS

Candidate Series-Connected Hybrid Power Trains

Three series-connected hybrid configurations were studied in detail: a full voltage system in which the alternator voltage is maintained at the battery bus voltage, a two-generator scheme in which one alternator feeds the battery while the other machine feeds the traction motor, and an alternator PCU system in which the alternator voltage is boosted by power processing to battery bus voltage. Details of preliminary comparative analyses, block diagrams and description of operation are found in Section 2.0.

Table I summarizes the results of the analyses. The alternator PCU system suffers from the inefficiency of two tandem power processors as well as additional expense and volume associated with a boost PCU capable of controlling the full engine output power.

Of the other two systems, the two-generator scheme offers slightly higher efficiency. However, it appears to have some potential control complexity problems, such as the need for specific alternator control sequencing to insure proper sharing of engine power. The full voltage series system was therefore selected for further analyses.

The parallel hybrid power train selected for study was the Electromechanical Transmission developed by TRW Systems.

Selection and Characterization of Power Train Components

The following comprise the major power train components which had to be selected and characterized for computer simulation:

- traction motors
- power control units, (PCU)
- rectifiers
- alternators
- batteries
- mechanical gearing
- internal combustion engine (heat engine)

TABLE I

COMPARISON OF THREE CANDIDATE SERIES-CONNECTED HYBRID POWER TRAINS

System	Total Weight (lb)	System Efficiency No Power Transfer from Battery Efficiency at 21 mph (%)	Efficiency at 42 mph (%)	Efficiency at 60 mph (%)	Efficiency at 85 mph (%)	Battery Impact Power to* Battery at 22 mph Cruise, kw	Power from** Battery at Mean Max Pwr 23 kw	Power PCUs	Control Complexity
Full Voltage Series	705	28.0	56.4	66.0	75.5	+1.82	-26.10	one	dual loop
Two Generator System	691	38.5	60.5	71.5	77.0	+2.81	-26.80	one	multi loop
Alternator PCU System	697	30.0	49.0	60.0	71.0	+1.1	-26.9	two	dual loop

*Refers to the power available to the battery due to excess of engine power over road cruise power. The larger the number, the more efficient is the path from engine through generator to battery terminals (see section 2.3.1).

**Refers to the peak burden placed on battery during an average urban acceleration. The lower the peak, the more efficient the traction system and the higher the utilization of engine power converted in the generator (see section 2.3.1).

Internal combustion engine requirements are briefly discussed in Appendix B. Estimates of power train efficiency suggested a peak horsepower output of about 85 hp. An examination of internal combustion engine fuel economy and emissions suggested a 3:1 speed variation over the full range of vehicle speeds.

The characteristics of lead-acid batteries were reviewed. Based on data supplied from work conducted, the contract "Development of High Rate Lead-Acid Batteries for Hybrid Vehicles," EPA contract no. 68-04-0028, $86 \times 10^{-3}\ \Omega$ was chosen as a reasonable total impedance for advanced, high power density batteries. Impedances two and three times greater were also selected to reflect changes in battery charge state and aging. An open circuit voltage of 240 VDC was assumed to be required.

The continuous high speed cruise traction power required of a 4000 pound family car provides the nominal rating for the series hybrid motor specification. The motor for the parallel system was rated on the basis of average power and torque demands from analysis and previous experience with EMT dynamometer tests. Contacts were established with a variety of motor manufacturers including H.K. Porter, Westinghouse, GE and Lear Siegler. These contacts established a preliminary motor configuration and machine characteristics which are to be found in Appendix D.

Power control units specifications were developed from analyses of PCUs which were designed for the EMT and could be used in either series or parallel hybrid power trains. Two motor PCU units were specified and rated according to peak current capability. The ratings reflected the possible use of variable gear ratios between the motor and wheels to lower the peak motor torque and current below the levels which would be encountered with a single gear ratio. Detailed specifications and efficiency computations of the PCUs can be found in Appendix E.

Three alternator designs were investigated, one using forced air cooling, another using an integral fan and the third using oil spray cooling with external heat transfer equipment. Oil cooling was rejected as it is usually associated with machines designed for extremely high power densities where efficiency is of secondary concern. One of the study guidelines was to use machinery possessing high efficiency and oil cooled designs did not appear to fulfill this requirement.

the series system alternator suggested the use of an integral fan. Over a narrow speed range an integral fan can be designed to provide the cooling air flow without low speed inefficiency. In the parallel system, the alternator operates over a 10:1 speed range at constant armature current. An external, constant air flow cooling system is preferred.

The gear efficiencies for the various systems were estimated from data published in standard engineering handbooks. Wherever necessary the efficiencies were slightly degraded as functions of increasing mesh speed to reflect possible higher viscous losses with speed. The planetary gearing of the parallel system was more difficult to analyze in that it is not clear what specific design or means of lubrication would be chosen. For these reasons, planetary gear efficiency was treated as a variable which could take on values thought to bracket planetary performance.

Extensive computer models and analysis techniques were developed. The bounds of possible vehicle operation were defined in terms of peak acceleration/deceleration rates from zero to 80% of the vehicle's top speed of 85 mph. A matrix of velocity-acceleration-road power demand points was computed within these bounds. In addition, the probability of each specific matrix point (a point represented the midpoint of a small velocity and acceleration increment about the matrix point) for driving the LA-4 cycle was computed.

The series and parallel systems were mathematically modeled and computer programs were developed. The models and programs are fully explained in Appendix F.

Evaluation of Instantaneous and Average LA-4 Performance of the Series and Parallel Hybrid Power Trains

The state of important performance measures of each of the major components of the selected parallel and series systems were calculated for each matrix point. The above-mentioned component characteristics were used in the computations. Engine power levels, gearing and battery characteristics were selected on the basis of preliminary analyses and experience.

Complete sets of instantaneous component efficiencies for typical series and parallel input parameters can be found in Appendix G.

System and component average and RMS performances were computed by using matrix point performance measures and matrix point probabilities and making appropriate averaging and root-mean-square computations. A description of the techniques are found in Appendix F.

Overall system efficiencies for LA-4 operation are summarized in Table II. System efficiencies are indicated as functions of the major input parameters of battery impedance, gear train efficiency and degree of gear ratio variation between the traction motors and wheels. In each case, the state of charge of the battery remained constant over the driving cycle.

Figures 5.1, 5.2, 5.3, 5.4 and 5.5 show block diagrams of the full voltage series system along with average efficiency and input/output power levels generated from the LA-4 cycle. Figures 5.6, 5.7, 5.8, 5.9 and 5.10 present similar information for the parallel system.

A variable gear ratio between the traction motor and the differential was shown to substantially increase the overall system efficiency of both configurations. The improvement was as much as 15% for the series and 13% for the parallel.

Regeneration was also important in raising the overall system efficiency; by as much as 10% in the series system and 13.5% in the parallel. Battery impedance variation has little effect on the parallel system; doubling the impedance decreases the series system efficiency by about 7%.

The planetary gear efficiency of the parallel system is important to the performance of that type of power train. An 11% change in efficiency decreases the overall system efficiency by a similar amount.

The design ratings of all the rotating machines and PCUs were conservative for LA-4 operation as long as a variable gear ratio was used for the parallel system. The series system motor and motor PCU are designed for higher continuous power than those of the parallel and thus the impact of variable gearing on their rating is lessened.

TABLE II

SUMMARY OF HYBRID SYSTEMS EFFICIENCY ON LA-4 DRIVING CYCLE

	Battery Impedance Ω	Motor to Wheel Gear Patio	Planetary Gear Nominal Efficiency	Regenerative Braking	Overall Efficiency
Full Voltage Series System	86×10^{-3}	constant	---	yes	47.9
	86×10^{-3}	variable	---	yes	55.1
	86×10^{-3}	constant	---	no	42.9
	172×10^{-3}	variable	---	yes	52.0
	172×10^{-3}	variable	---	no	46.4
Parallel (EMT) System	86×10^{-3}	constant	80%	yes	61.7
	86×10^{-3}	constant	80%	no*	53.6
	86×10^{-3}	variable	90%	yes	76.7
	172×10^{-3}	variable	80%	yes	66.6
	172×10^{-3}	variable	80%	no*	54.0

*Regenerative braking capability in the EMT is a normal part of its control system.

Weight and Cost Estimates of Hybrid Power Trains

The OEM cost of the series system is estimated to be $768; the parallel system will cost $600, both exclusive of battery and engine. Assuming 500 pounds of lead-acid batteries and a 350 pound engine, the parallel system will weigh between 1451 and 1501 pounds. The series system will weigh 1649 to 1699 pounds. In each case, the heavier value includes the incorporation of a variable gear ratio transmission.

While new car customer costs of hybrids cannot be estimated at this time, it appears that the fuel savings would be able to pay for battery replacement costs. Furthermore, the durability and modular packaging of the electrical equipment may lead to novel power train marketing and recycling such as "portable" PCUs where the control electronics is owned by the customer and he transfers it from one vehicle to another as he changes cars.

EXPERIMENTAL ACTIVITIES

Experimental studies were conducted on the effectiveness of selected internal combustion engine emission control concepts used within the context of hybrid vehicle operation. The usefulness of the devices depended on controlled engine operation during start-up and hot operation and therefore, could not be applied to a first approximation to conventional IC powered vehicles where driveability demands would interfere with engine-control system operation.

Hydrocarbon Accumulator Materials Screening

The first device studied was a hydrocarbon accumulator which operates on an adsorption-desorption cycle. It is based on well-developed chromatographic principles of organic compound separation. The accumulator material adsorbs engine exhaust hydrocarbons from the relatively cool exhaust stream during engine start-up and retains them as the exhaust temperature rises and the engine choke is relieved. When the exhaust or bed temperature reaches a predetermined point, a large portion (~99%) of the exhaust is diverted through a jacket around the accumulator; the remaining exhaust flows through the accumulator, picking up hydrocarbons and returning them to the engine intake or catalytic converter for combustion.

The selection of the most promising hydrocarbon accumulator material was carried out by a material screening process. The materials tested were, in order of decreasing effectiveness, activated carbons, activated charcoals, molecular sieves, silica gels and aluminas. Test materials were placed within a canister downstream of the exhaust port of one single cylinder of a 1600 cc VW engine. Cold start tests were carried out to assess the retention and desorption properties of each of the materials. The materials were also investigated for chemical and mechanical degradation.

Tests indicated that activated carbons are the most efficient class of materials within the range tested. They exhibit the highest capacity for exhaust hydrocarbons at a given temperature and are capable of continued adsorbing nearly twice the hydrocarbons of the next best material. Even at space velocities in excess of 80,000 V/V/Hr and exhaust temperatures as high as 600°F, one material, Pittsburgh Activated Carbon, BPL series, did not show chemical or mechanical deterioration after several absorption-desorption cycles as long as care was exercised when the accumulator was being filled.

Characterization of TRW-Harshaw Three-Component Catalyst

A copper oxide-on-alumina catalyst was evaluated for use as a three-component catalyst, that is one which simultaneously controls hydrocarbons (HC), carbon monoxide (CO) and nitric oxide (NO). The catalyst is manufactured by Harshaw Chemical Co. and is activated by a TRW process.

Bench scale tests on the catalyst showed that:

- it could convert about 90% CH_4 and NO and 100% CO in a synthetic exhaust gas mixture
- the CO oxidation process started aro[illegible]°F, NO reduction around 500-650°F and methane oxidatior [illegible] 1000°F.

Catalyst conversion tests were conducted using a ca[illegible]aining about 100 in^3 of catalyst. The bed was exposed to the flow [illegible] same cylinder as in the hydrocarbon accumulator tests. The tests sho[illegible], in steady state:

- The catalyst is generally non-selective in promoting the reaction of exhaust components. At temperatures around 1200°F CO oxidation is favored over HC; the opposite is true above 1500°F. However, other reactions are presumed to cause these effects rather than catalyst selectivity.

- The catalyst can reduce the levels of all three pollutants simultaneously by 75% for bed temperatures in excess of 1350°F and in an air-fuel ratio band of 0.7.
- Relative conversion of HC and CO are temperature dependent.
- Space velocity effects the conversion efficiencies on an individual basis. At stoichiometry NO conversion decreases from 90% to 70% as the space velocity increases from 32,000 to 37,000 V/V/Hr. While HC and CO conversions were unaffected by space velocity at that air-fuel ratio, they become space velocity sensitive for richer mixtures.
- Chemical effects and non-selectivity work to limit the catalyst effectiveness. It appears that the air-fuel ratio point of maximum simultaneous conversion moves to leaner mixtures with increasing temperature.

The catalyst will tend to suffer reduced NO conversion efficiency with time when exposed to lean mixtures. However, the time constant of the loss is on the order of minutes. Also the catalyst recovers its initial capability almost immediately when exposed to a slightly rich mixture. Thus the catalyst will provide effective control to short duration swings in the mixture ratio.

Steady state tests on the full exhaust stream of a Vega ICE were conducted using a scaled-up version of the single cylinder converter. Scaling up the converter by a factor of four slightly increased the band of effective CO conversion; the other conversions were unaffected.

Data comparing engine hydrogen generation and catalyst ammonia production suggested there was no direct link between them. There is a strong dependence of ammonia generation on temperature and air-fuel ratio. At A/F levels below 13, NH_3 approaches 100% of the total reacted NO, thus all the NO goes into producing NH_3. However, in the A/F and temperature band where the catalyst must function for good three-component control, NH_3 production is always less than 10% of the reduced NO.

Physical changes in the catalyst were small, if any, over the period of testing. The cost and catalyst bed size for a full size converter are well within practical limits. The estimated catalyst cost for a full size passenger vehicle is around $10 to $15; the estimated catalyst volume is 0.2 cubic feet.

Two catalytic converters supplied by Universal Oil Products were tested. While the converters showed good CO and HC oxidation characteristics at lean air-fuel ratios, the peak NO conversion did not exceed 40%. It is possible that the converters were too small for this application.

Full Scale Hybrid Power Train Emissions

The emissions of a hybrid power train were measured for the system operating over the 1972 Federal driving cycle and using the cold start, constant volume sampling "bag" technique. The engine ran over a power schedule simulating the load demand which would be required in a real hybrid vehicle.

An emission control system using a fast relief choke schedule, hydrocarbon accumulator and three-component catalyst was able to bring the system emissions below the 1975-76 standards. Hydrocarbons ranged from 34% to 73% of the 1975 standards; NO_x was 15% to 80% of the 1976 levels. CO proved to be the most troublesome component. While the 1975 standard for CO was met, it is felt that improved carburetion during cold start would have increased the margin by which the CO standards would be satisfied.

While long term testing has not been performed to demonstrate the ability of the control approach to meet the standards for 50,000 miles, short-term evaluation involving about 100 hours of testing has shown good chemical and physical stability of the materials used in both control devices.

1.0 INTRODUCTION

Heat engine/battery hybrid automotive power systems have been under investigation by TRW Systems since 1967. As part of a company-funded effort a parallel hybrid configuration termed the Electromechanical Transmission (EMT) was conceived and a full-scale power dynamometer proof-of-principle breadboard system was constructed and demonstrated. A description of the EMT as well as experimental data taken on the system was previously reported in the EPA-sponsored contract, "Analysis and Advanced Design Study of an Electromechanical Transmission," No. EHSH-71-002, April 1972 (reference 1).

Hybrid power systems appear attractive for low emission, high fuel economy vehicles. However, several questions related to the selection of the best hybrid system, cost of such systems and the emission levels of such vehicles remain.

In order to resolve many of these questions, TRW Systems has been under contract (No. 68-04-0058)to the Division of Advanced Automotive Power Systems Development, Office of Air Programs, Environmental Protection Agency to perform "Cost and Emission Studies of a Heat Engine Battery Hybrid Family Car." The period of performance was June 30, 1971 to February 29, 1972. The latter date was extended approximately one month to cover additional experimental measurements not originally called for in the contract.

Among the objectives of the contract were the development of detailed models of candidate heat engine-battery hybrid power trains for full size family cars, analysis of the efficiency of the candidates and an estimation of the size, first cost and cost of ownership of such vehicles. A second phase of the work was a laboratory investigation of the characteristics and suitability of three-component catalytic devices and hydrocarbon traps as means for controlling internal combustion engine emissions within the context of a hybrid environment. The goal of the experimental work was to demonstrate that a full-sized hybrid system could meet the 1975-76 emission standards.

This report is organized into two basically different sections, reflecting the extensive analytic and computer simulation work as well as laboratory effort. It will be necessary to utilize data from one section in the other in some cases; whenever this occurs, the reader will be alerted.

The report contains a large number of appendices in which the background and supporting calculations which are necessary for a full understanding of the report results are to be found.

2.0 SELECTION OF CANDIDATE SERIES-CONNECTED HYBRID POWER TRAINS

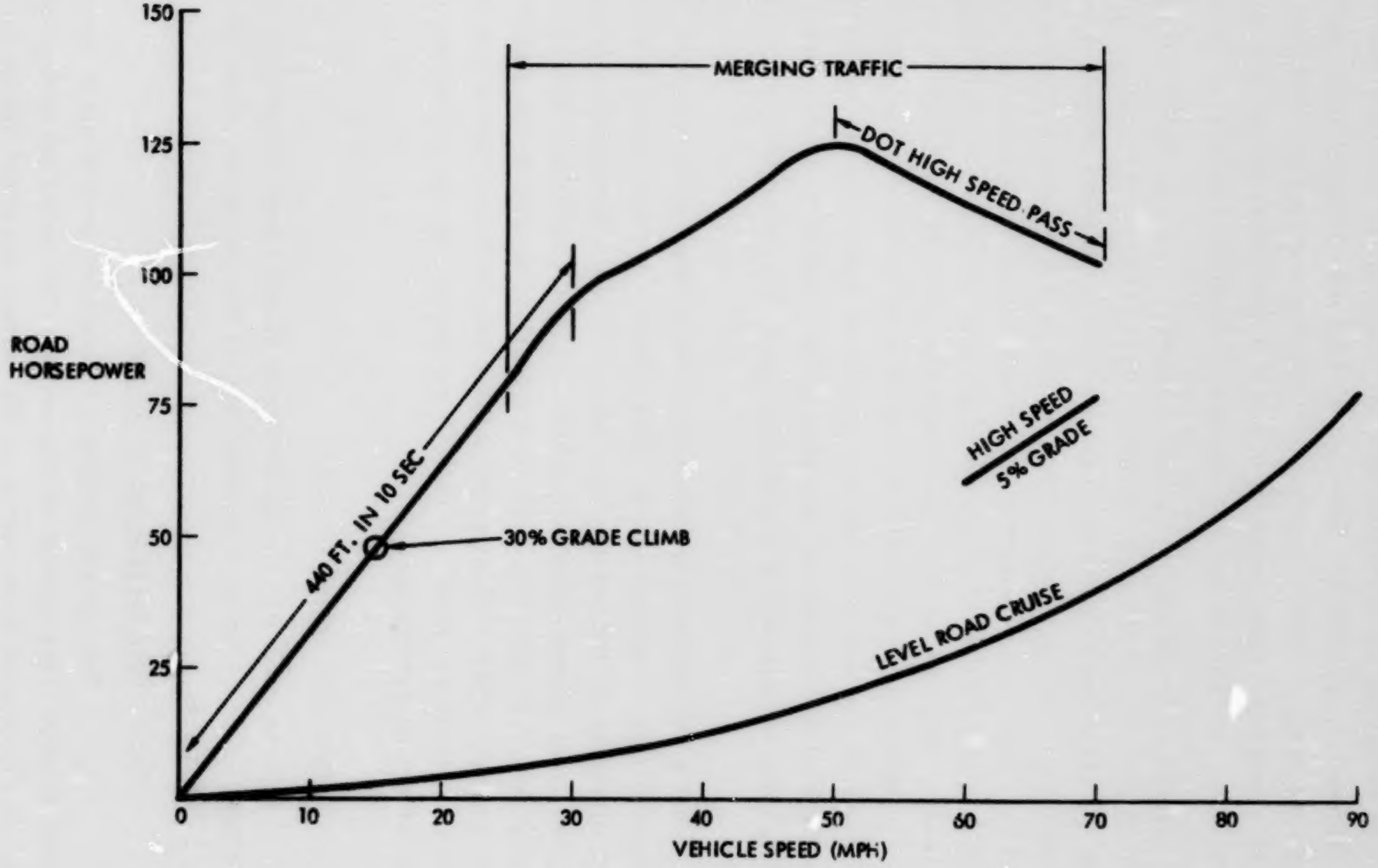
2.1 General Specifications and Assumptions

The initial phase of vehicle power train selection must start with a definition of the loads and modes of operation which a power train will encounter in service. The Office of Air Programs has prepared a complete set of vehicle design goals for a passenger car which will have the performance, safety, convenience and ease of operation which may be necessary to satisfy the requirements of the average motorist. These design goals also specify that the vehicle be capable of meeting the Federal emission standards for 1975-76 established by the 1970 Clean Air Act. The design goals may be found in Appendix A.

The interpretation of the performance goals into wheel power loads depends on the detailed vehicle velocity-time schedule of the specified maneuver, say the high speed pass maneuver. Using some assumptions as to the nature of the schedule, the wheel power demands for a 4000 pound family car having the drag characteristics stated in the Design Goals can be computed. Figure 2.1 shows the level-road and peak cruise requirements as a function of vehicle velocity along with some grade requirements. To cruise at 85 mph, approximately 65 road horsepower is needed and the power train must be capable of providing short duration wheel power bursts in excess of 100 horsepower. If it is assumed that the power train elements between the engine and wheels have an overall efficiency of approximately 75% and with allowance for passenger comfort and convenience features, the engine must be capable of continuously supplying about 85 shaft horsepower at 85 mph cruise.

FIGURE 2.1

WHEEL POWER DEMANDS FOR A 4000 LB CAR



The selection and specifications of an engine for a hybrid system are reviewed in Appendix B. Economy and emission characteristics combine to set the range of engine displacement and its speed range. The series system's generator speed range is directly proportional to the engine speed range; for this study a 3:1 generator (engine) speed range is assumed.

Several other general criteria for operation must be specified before starting analyses of the power trains. These refer to the modes of power train operation and in particular the demarkation between urban and highway operation. We shall assume that at one-half the vehicle's top speed, 42.5 mph, there is a departure point between urban and highway operation. In urban traffic below 42.5 mph the engine will operate at constant power and speed. When the vehicle speed increases above 42.5 mph, it is assumed that the engine speed will linearly increase up to its maximum value corresponding to the vehicle's top speed. At the same time, the engine's throttle will be adjusted so that the engine's output times the power train inefficiency between engine and wheels equals the road cruise power at that speed.

Finally, performance analyses of a hybrid power train must consider the possibility of battery charge state change. A power train which causes a net discharge of the battery does not fulfill all the design criteria; one that tends to overcharge the battery will be inefficient and might cause battery damage in the field. It is difficult to establish the engine power level a priori which will keep the battery near constant charge and one must use a trial and error approach in evaluating various parameters and their effect on performance.

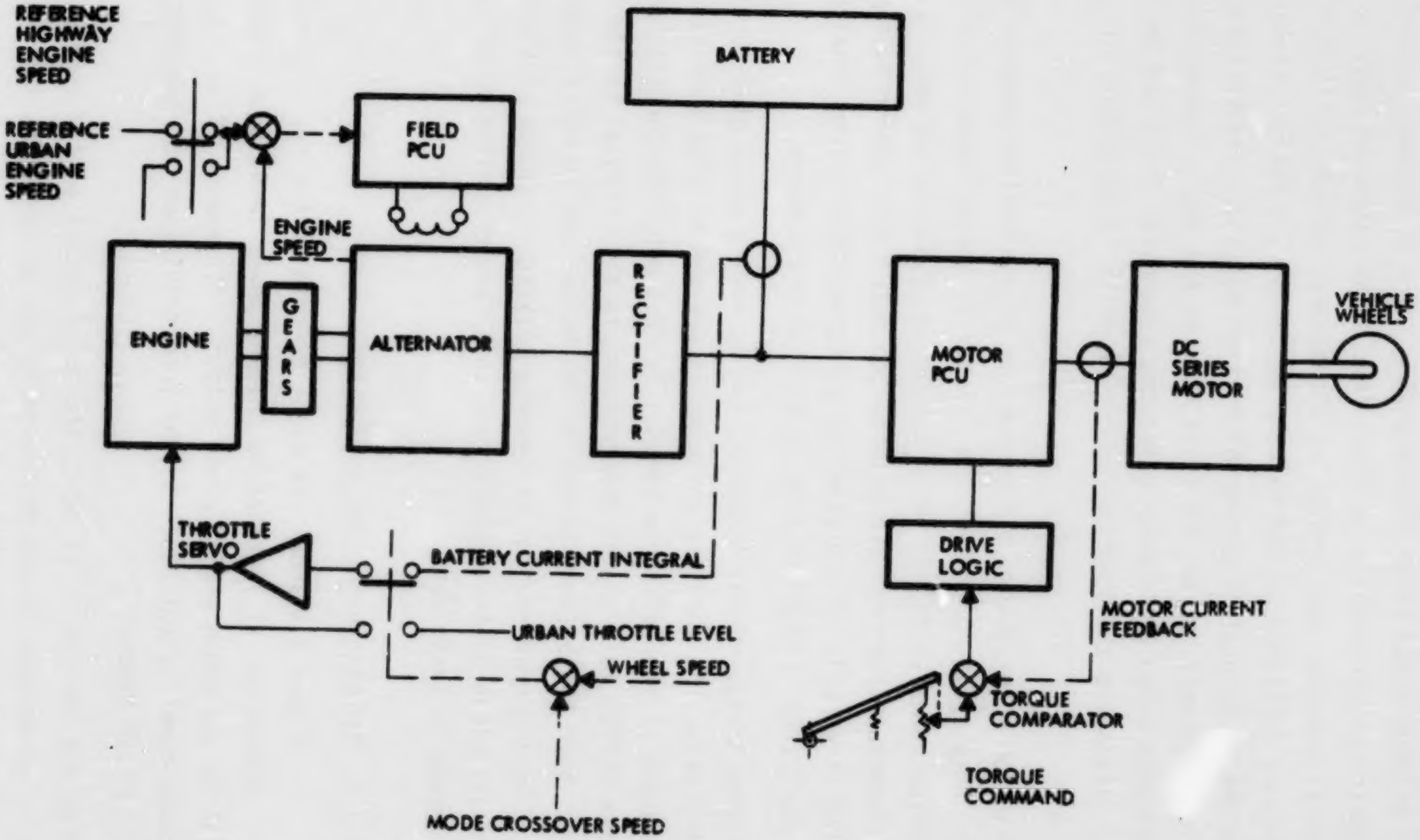
2.2 Candidate Series Systems

Three candidate series-connected hybrid power trains were selected for study. Block diagram representations of the system are shown in Figures 2.2, 2.3 and 2.4.

2.2.1 Full Voltage Series System

This system (Figure 2.2) contains an alternator directly coupled through fixed gearing to the engine. The rectified voltage and power of the machine is delivered to the battery bus where the power can be used to either charge the battery or power the traction motor. The

FIGURE 2.2
FULL VOLTAGE SERIES-CONNECTED HYBRID SYSTEM


REFERENCE HIGHWAY ENGINE SPEED
REFERENCE URBAN ENGINE SPEED
FIELD PCU
BATTERY
ENGINE SPEED
ENGINE
GEARS
ALTERNATOR
RECTIFIER
MOTOR PCU
DC SERIES MOTOR
VEHICLE WHEELS
THROTTLE SERVO
BATTERY CURRENT INTEGRAL
URBAN THROTTLE LEVEL
WHEEL SPEED
MODE CROSSOVER SPEED
DRIVE LOGIC
MOTOR CURRENT FEEDBACK
TORQUE COMPARATOR
TORQUE COMMAND

alternator runs at one-third its rated speed in urban traffic reflecting the 3:1 maximum speed range of the engine. During highway operation its speed varies proportionally to road speed. The output voltage of the alternator, however, must remain at the battery voltage so that alternator power can be delivered to the battery bus. Thus, a field control system is required to maintain a proper alternator voltage. Feedback engine speed control is accomplished by the field PCU; as the engine speed rises above the reference urban or highway value the alternator field and voltage increase, increasing the load on the engine which in turn tends to slow the engine down.

Traction motor power is processed by a regenerative chopper motor PCU(1). Duty cycle control of the chopper is accomplished through a drive logic which compares the driver's torque command with the motor's developed torque (armature current) and adjusts the duty cycle appropriately. The motor PCU is capable of operating as a regenerative system, taking motor (generator) power and processing it back to the battery.

Engine torque output is controlled by moving the engine throttle. In the urban mode, the throttle position is pre-set to give some assigned power output at the reference speed. At 42.5 mph, the throttle position reference shifts to a signal proportional to the integral of the battery current. When the battery begins to discharge, the throttle opens very slowly. During regeneration or dynamic braking it closes slowly. All the systems described in this report have this form of engine power control incorporated in their design.

2.2.2 Two Alternator Series System*

Figure 2.3 shows the block diagram of the two alternator system. Alternator #1 is rated at a lower power level than alternator #2 equal to the urban engine power output. Alternator #2 is rated for a continuous power output equal to the load requirement of the traction motor at top vehicle speed.

When the vehicle is at rest, the total output of the engine is processed by alternator #1 and delivered to the battery. As the operator accelerates the car, the field of alternator #2 increases and the field

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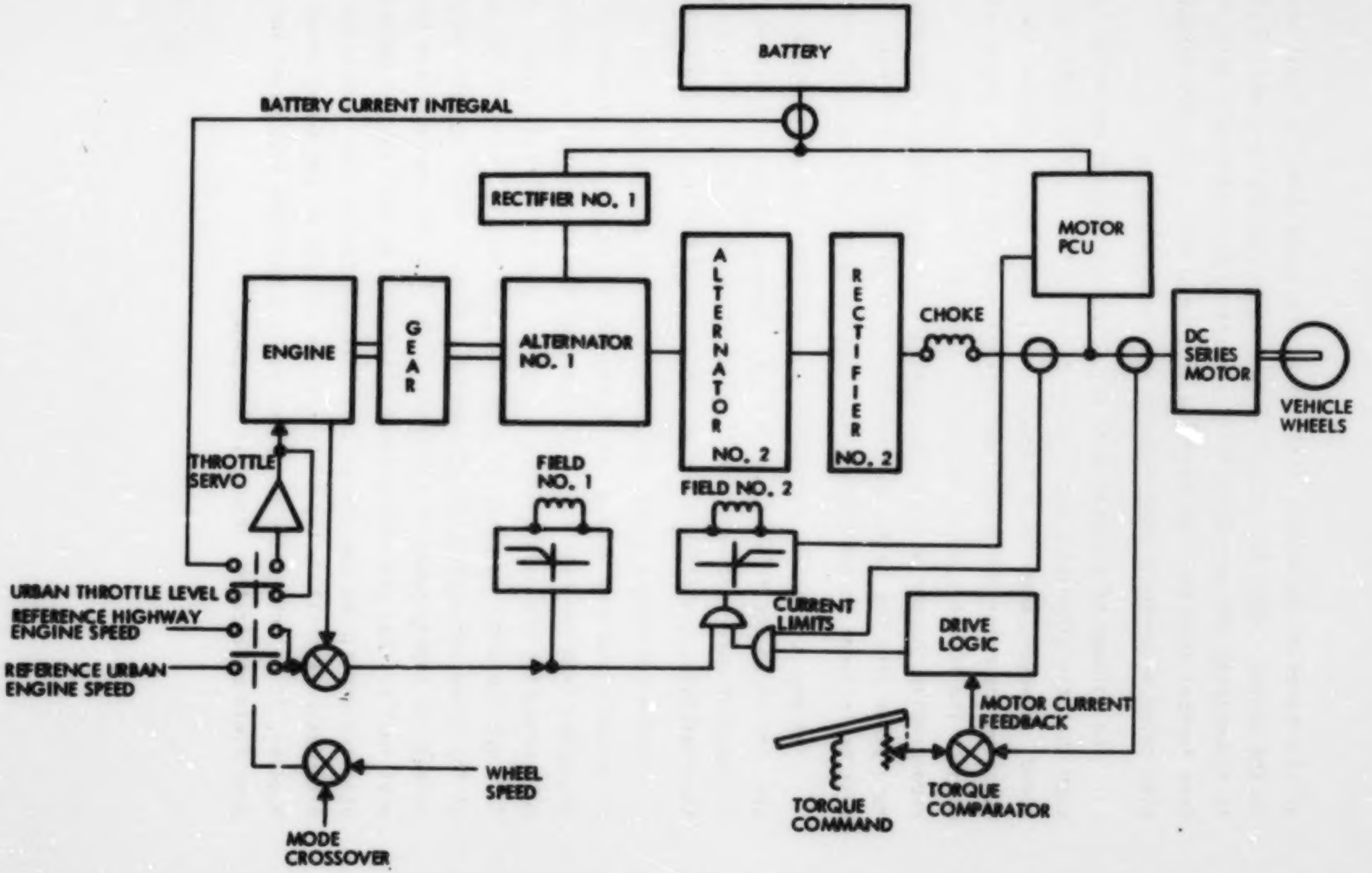
*The Two Alternator configuration was suggested for study by Dr. Jalal Salihi of EPA.

FIGURE 2.3
TWO ALTERNATOR SERIES CONNECTED HYBRID SYSTEM


BATTERY
BATTERY CURRENT INTEGRAL
RECTIFIER NO. 1
MOTOR PCU
ENGINE
GEAR
ALTERNATOR NO. 1
ALTERNATOR NO. 2
RECTIFIER NO. 2
CHOKE
DC SERIES MOTOR
VEHICLE WHEELS
THROTTLE SERVO
FIELD NO. 1
FIELD NO. 2
CURRENT LIMITS
DRIVE LOGIC
URBAN THROTTLE LEVEL
REFERENCE HIGHWAY ENGINE SPEED
REFERENCE URBAN ENGINE SPEED
MOTOR CURRENT FEEDBACK
WHEEL SPEED
MODE CROSSOVER
TORQUE COMMAND
TORQUE COMPARATOR

of alternator #1 decreases, shifting engine power from the first machine to the second. When the output of #2 reaches the engine power, field #1 is essentially off and field #2 is prohibited by a threshold detector from further increase. At very low vehicle speeds, a current detector on alternator #2 protects that machine against overloading.

The voltage of alternator #2 is controlled through the drive logic such that the alternator can deliver power to the traction motor at any speed. However, when the alternator's current limit is reached the logic turns on the motor PCU and allows battery power to flow to the traction motor. The PCU is similar to that of the full voltage system--it is a regenerative chopper drvice. Increasing the chopper duty cycle draws more power from the battery/alternator #1 power sources. A choke, L, must be included in the circuit for continuity of alternator #2 current.

The engine throttle control system and motor torque feedback controls are similar to the full voltage system. However, the engine speed control is somewhat more complex in that the fields must be adjusted in a manner that maintains stability and restricts speed excursions of the engine.

While the single alternator of the full voltage system must be capable of producing battery voltage at one-third its top speed, alternator #2 is uncoupled from the battery bus voltage and therefore need be capable of only producing one-half battery voltage at one-third rated speed. (At 42.5 mph the motor terminal voltage is approximately one-half its voltage at top speed and alternator #2 need only produce power at half battery voltage to supply power to the motor.) Machine #2 therefore can be somewhat smaller than the full voltage alternator as its field is better utilized and can be run closer to saturation during urban operation. Alternator #1 still must produce battery voltage at one-third rated speed; however, it is inherently a smaller machine handling less power and the poor field utilization impact is lessened.

2.2.3 Series System with Alternator PCU

The series system with alternator PCU is an attempt to reduce alternator size requirements by running the alternator field around saturation independent of the machine's speed. The alternator is coupled to a voltage boost type PCU as shown in Figure 2.4. In almost all other respects its operation and control is the same as the full voltage system.

The boost PCU incorporates an inductive energy storage element which is first charged from the alternator and then discharged in series with the alternator into the battery bus. This technique of alternator control has been successfully employed on the EMT dynamometer demonstration and is utilized for regenerative power control on all the three series traction motor systems. A further description of the boost PCU technique can be found in reference 1.

Duty cycle input control of the boost PCU is accomplished through an alternator PCU controller. It processes engine speed error signals similarly as the other systems but instead of changing the alternator's field, it adjusts the PCU duty cycle.

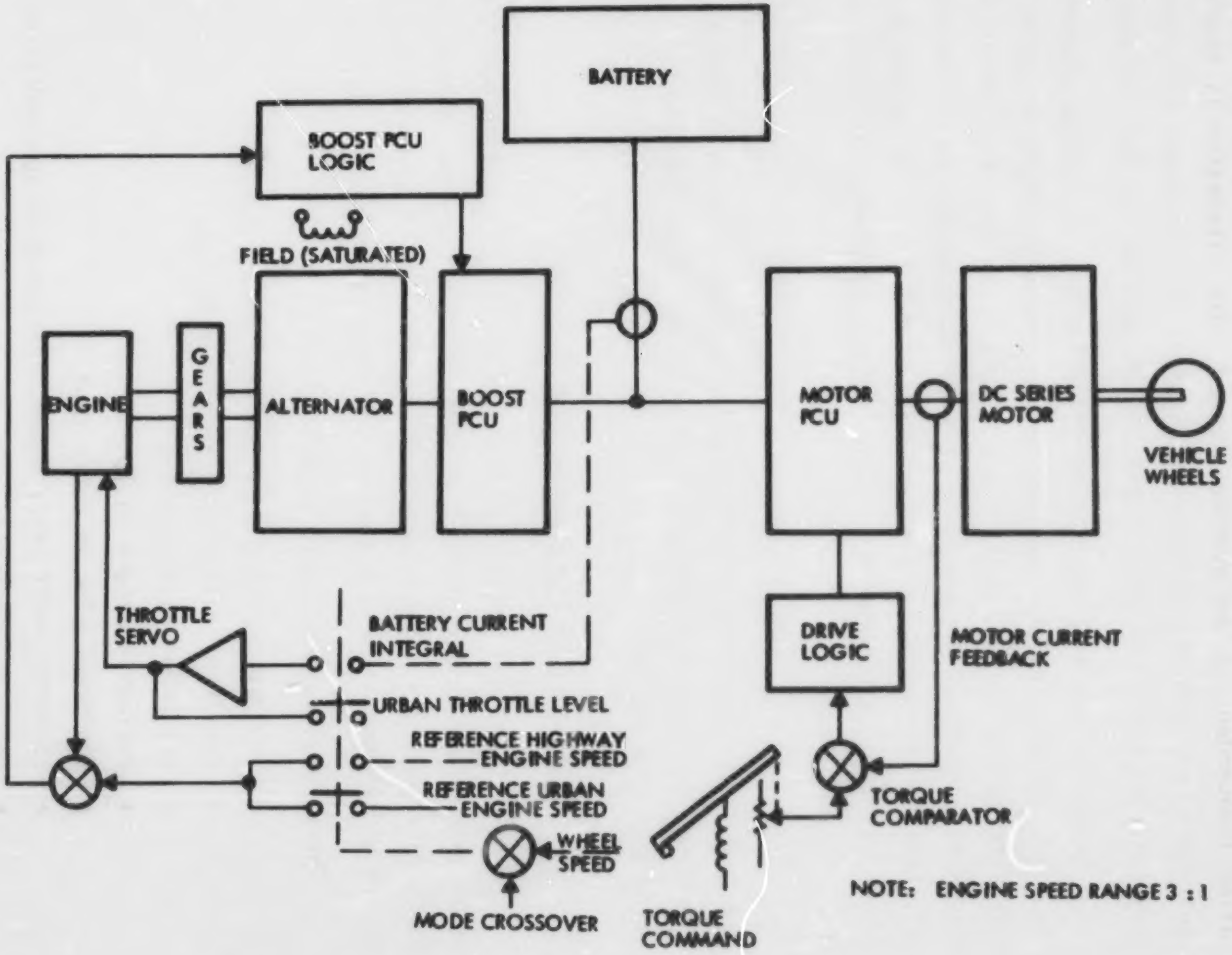
2.3 Evaluation of Candidate Series Systems

Preliminary specifications for the major rotating machines and power processors were developed in terms of the required vehicle performance of Figure 2.1. Each component is specified in terms of the parameters which impact the greatest on the final selection.

The parameters which were used are:

- equipment rating on a per unit (p.u.) basis
- equipment rating on a kw and/or hp basis
- equipment rating in KVA
- equipment weight in lb
- equipment size in cubic feet
- equipment efficiency under selected driving conditions
- equipment projected cost
- equipment control simplicity and reliability.

FIGURE 2.4
SERIES HYBRID SYSTEM WITH ALTERNATOR PCU


BATTERY
BOOST PCU LOGIC
FIELD (SATURATED)
ENGINE
GEARS
ALTERNATOR
BOOST PCU
MOTOR PCU
DC SERIES MOTOR
VEHICLE WHEELS
DRIVE LOGIC
MOTOR CURRENT FEEDBACK
TORQUE COMPARATOR
THROTTLE SERVO
BATTERY CURRENT INTEGRAL
URBAN THROTTLE LEVEL
REFERENCE HIGHWAY ENGINE SPEED
REFERENCE URBAN ENGINE SPEED
WHEEL SPEED
MODE CROSSOVER
TORQUE COMMAND

NOTE: ENGINE SPEED RANGE 3 : 1

Power rating of equipment on a per unit (p.u.) basis allows a first order qualative comparison between a multitude of systems which would operate at different rated power levels.

Unity per unit is defined as the inherent rated physical capability designed into the equipment. For quantitative evaluation, the ratings are determined in absolute units of kilowatts or horsepower. For example, in this study the full load motor rating is 65 hp at 85 mph.

Thus, 1 p.u. power for the traction motor is 65 hp, 1 p.u. voltage is the battery open circuit voltage and motor current at 65 hp and battery voltage is 1 p.u. machine current. The power ratings are pivotal for the efficiency computations.

The nature of the load transients, out of phase current, voltages and rectification are such as to impact the equipment rating in a manner analogous to that derived from power factor loads. The ratings which reflect the capability of units operating under non-ideal conditions are given in KVA and are very important for computations of component size, weight and cost.

Figure 2.5 repeats the vehicle performance requirements of Figure 2.1; however, superimposed are the current requirements for a motor rated at 65 hp, 360 VDC, 194 amperes, at 5000 rpm with an efficiency of about 90%. This machine, initially chosen for preliminary system comparison, would represent advanced state-of-the-art machinery and would be of a lightweight design so that it could produce about 0.2 hp/lb. The specification for the alternators depend on the specific system under consideration. Appendix C treats these specifications along with PCU requirements.

Tables 2.1, 2.2, 2.3, 2.4, 2.5, and 2.6 summarize the specifications of the major units. In all three systems, the use of an oil spray cooled alternator was investigated as a means for increasing the power density of that component.

FIGURE 2.5
PER UNIT TORQUE REQUIREMENTS OF THE TRACTION MOTOR FOR SERIES-CONNECTED HYBRID SYSTEMS

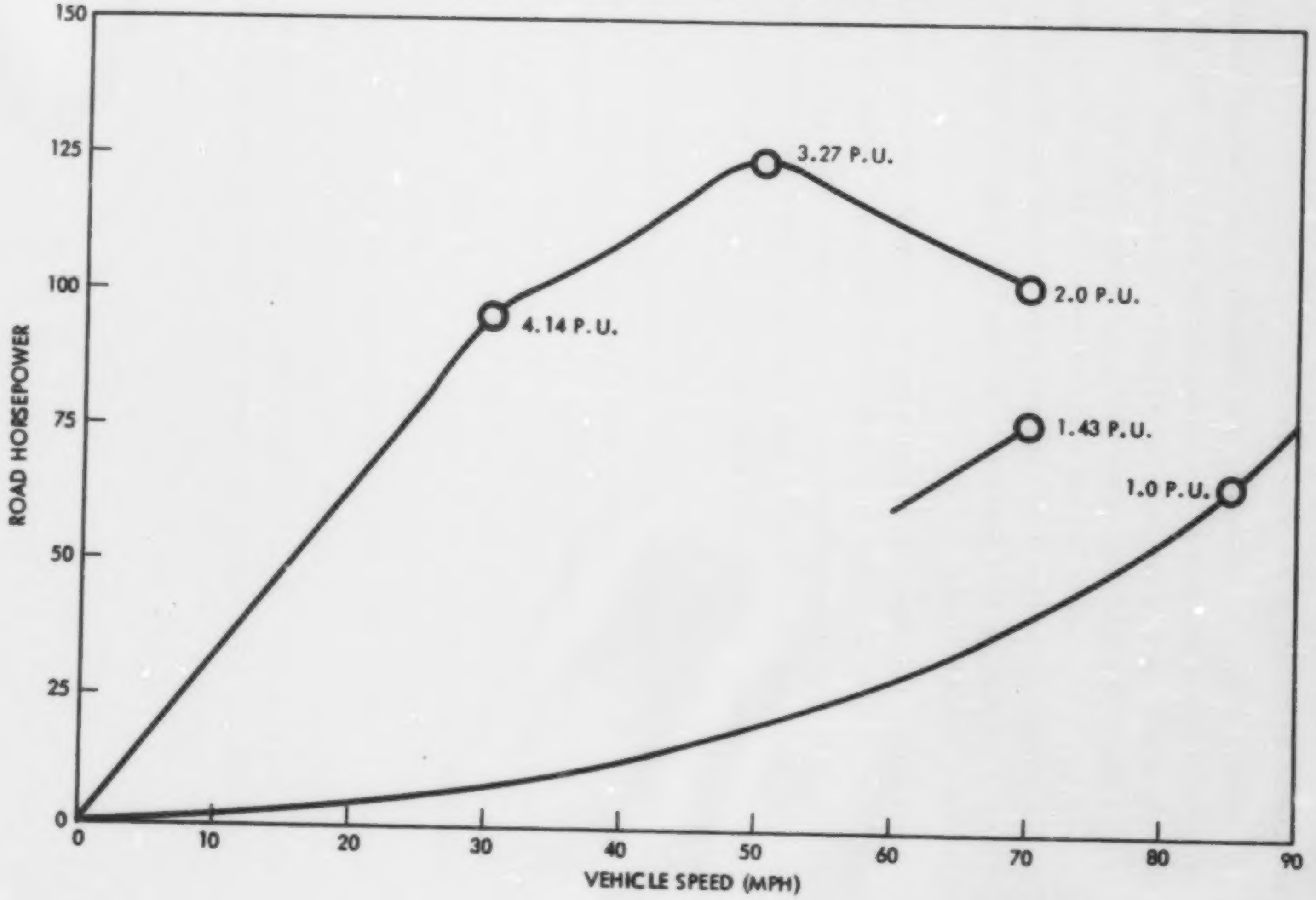


TABLE 2.1

PRELIMINARY SPECIFICATIONS OF FULL VOLTAGE SYSTEM USING FORCED COOLED ALTERNATOR

	Input	Alternator	Rectifier	PCU	Motor	Total
Rating at Base Speed (p.u.)	1	3	1	1	1	
Rated Power Level	64.5 kw	58x3 kw	57.5 kw	54 kw	65 hp	
Efficiency at Top Vehicle Speed	---	90	99.2	94	90	Total Series Efficiency 75.5%
Approximate KVA at Top Speed	---	61x3=183	57.5	272	---	---
Weight (lb)	30	230	---	120	325	705 lbs.
Size (cu. ft.)	---	1.05	Included within Alternator	2.0	1.27	4.32

TABLE 2.2

PRELIMINARY SPECIFICATIONS OF FULL VOLTAGE SYSTEM USING OIL SPRAY COOLED ALTERNATOR

	Input	Alternator	Rectifier	PCU	Motor	Total
Rating at Base Speed (p.u.)	1	3	1	1	1	
Rated Power Level	71.0 kw	58x3 kw	57.5 kw	54 kw	65 hp	
Efficiency at Top Vehicle Speed	---	82	99.2	94%	90%	Total Series Efficiency 68.6%
Approximate KVA at Top Speed	---	61x3=183	57.5	272	---	---
Weight (lb)	30	165	---	120	325	640 lbs.
Size (cu. ft.)	---	.92	within alternator	2.0	1.27	4.19

TABLE 2.3

PRELIMINARY SPECIFICATIONS OF TWO GENERATOR SYSTEM USING FORCED COOLED ALTERNATOR

	Input	Alternator #1	Alternator #2	Choke	Rectifier #1	Rectifier #2	PCU	Motor	Total
Rating at Base Speed (p.u.)	1	3	1.5	---	1	1	1	1	---
Rated Power Level	63.0 kw	3x10.2 kw	1.5x54.8 kw	---	10 kw	54 kw	20 kw	65 hp	---
Efficiency at Top Vehicle Speed	----	80 87	90	99	99.2	99.2	94	90	77.0
Approximate KVA at Top Speed	----	32.3	86.0	29.8	10	54	272	--	---
Weight (lb)	30	70.0	116	80	--	--	70	325	691 lb.
Size (cu. ft.)	----	0.55	0.75	.2	w/alternator	w/alternator	1.7	1.27	4.47

TABLE 2.4

PRELIMINARY SPECIFICATIONS OF TWO GENERATOR SYSTEM USING OIL SPRAY COOLED ALTERNATOR

	Input	Alternator #1	Alternator #2	Choke	Rectifier #1	Rectifier #2	PCU	Motor	Total
Rating at Base Speed (p.u.)	1	3	1.5	---	1	1	1	1	
Rated Power Level	62.5	3x10.2 kw	1.5x54.8 kw	---	10 kw	54 kw	20 kw	65 hp	
Efficiency at Top Vehicle Speed	----	73 80	83	99	99.2	99.2	94	90	71.0
Approximate KVA at Top Speed	65.6	32.3	86.0	29.8	10	54	272		
Weight (lb)	30	40.0	83	80	--	--	70	325	641 lb.

TABLE 2.5

PRELIMINARY SPECIFICATION OF SERIES SYSTEM WITH ALTERNATOR PCU USING FORCED COOLED ALTERNATOR

	Input	Alternator	Rectifier & Boost PCU with Storage Inductor	PCU	Motor	Total
Rating at Base Speed (p.u.)	1	1	1	1	1	
Rated Power Level	68.5 kw	61.6 kw	57.5 kw	54 kw	65 hp	--
Efficiency at Top Vehicle Speed	--	90	99.2x94=93.3	94%	90%	71.0%
Approximate KVA at Top Speed	--	64.6	57.5	272	---	--
Weight (lb)	30	102	120	120	325	697
Size (cu. ft.)	--	0.7	2.0	2.0	1.27	5.97

TABLE 2.6

PRELIMINARY SPECIFICATION OF SERIES SYSTEM WITH ALTERNATOR PCU USING OIL SPRAY COOLED ALTERNATOR

	Input	Alternator	Rectifier & Boost PCU	PCU	Motor	Total
Rating at Base Speed (p.u.)	1	1	1	1	1	
Rated Power Level	75.5 kw	61.6 kw	57.5	54 kw	65 hp	--
Efficiency at Top Vehicle Speed	--	82	99.2x94=93.3	94%	90%	65.5%
Approximate KVA at Top Speed	--	64.6	57.5	272	--	--
Weight (lb)	30	60	120	120	325	655
Size (cu. ft.)	--	0.55	2.0	2.0	1.27	5.82

2.3.1 Preliminary Selection - Criteria

The assessment of the three candidates is based on computing power train weights, volumes and efficiencies at selected operating conditions.

The first set of conditions termed "non-hybrid conditions" characterizes power train efficiency at selected speeds assuming there is no battery. Under these circumstances, the engine power must be computed so it can supply the vehicle's cruise power at the wheels taking into account power train losses. The road power demand at various vehicle cruise speeds is:

21 mph - 3.75 hp or 2.8 kw
42.50 mph - 15.00 hp or 11.2 kw
60.00 mph - 28.75 hp or 21.4 kw
85.00 mph - 65.00 hp or 48.5 kw

The second set of operating conditions which are analyzed involves using typical urban road power requirements to calculate battery charge and discharge power. The engine power is either held at a constant level in the urban mode or is allowed to throttle up to the road cruise demand of the highway mode. During the LA-4 runs (reference 1) a 4000 pound car required about 23 kw mean maximum road power for acceleration events. That is, if one computes the peak power required for each acceleration from rest, the average of the peaks is 23 kw. The average speed on LA-4 is about 21 mph and as shown above, the road demand at that speed is 3.75 hp. The system which draws minimum power from the battery during acceleration or is able to deliver largest charge power to the battery during cruise conditions would be preferred. For these preliminary calculations, a constant engine power level of 15 hp is assumed for vehicle speeds below 42.5 mph.

The computations for non-hybrid and hybrid conditions are found in Appendix C and are summarized in Table I of the summary section. Of the three systems, the series system with alternator PCU has the lowest overall efficiency. The two generator scheme offers slightly higher efficiency of the two other systems, however, its control is potentially more difficult. For example, the need to control both alternator fields in order to control engine power may cause stability problems in the electrical and mechanical loops.

TABLE 2.7

COMPARISON OF NON-HYBRID SYSTEM PERFORMANCE WITH OIL SPRAY-COOLED ALTERNATORS

System	Efficiency 21 mph (%)	Efficiency 42 mph (%)	Efficiency 60 mph (%)	Efficiency at top vehicle speed	Weight (lb)	Size (cu ft)
Full Voltage Series	21.0	51.5	60.4	68.6	640	4.19
Two Generator	24.6	57.0	65.0	71.0	641	4.22
Series w/alternator PCU	23.4	44.5	49.5	65.5	655	5.82

Oil spray cooled alternators were also examined as a part of the system selection process. Table 2.7 summarizes the non-hybrid cruise efficiency of power trains using this type of machine. The alternator PCU system has the lowest efficiency at higher vehicle speeds and was rejected. The efficiency comparison between the other two systems again favors the two generator system; however, there is a substantial loss in overall efficiency in both systems due to the use of the higher power density-lower efficiency alternator.

The full voltage series system with a forced air cooled alternator was therefore chosen as the candidate series system.

3.0 CHARACTERIZATION OF PARALLEL HYBRID SYSTEM

The parallel hybrid system selected for this study is the Electromechanical Transmission (EMT) system developed by TRW Systems. This power train has been described in reference 1 and therefore its modes of operation will be discussed only briefly.

3.1 Description of EMT

The EMT system consists of a planetary gear, alternator, alternator PCU, traction motor and motor PCU as shown in Figures 3.1 and 3.2. The engine input power drives the sun gear of the planetary set; the ring gear drives the power train propeller shaft and the planet carrier drives the alternator. The planetary gear algebraically divides the input power of the engine between the ring gear and planet carrier in direct proportion to the speeds of the respective elements. Thus, when the propeller shaft is stopped (car at rest), the planet carrier and alternator turn at maximum speed and all engine power goes into the alternator. As the car accelerates and the propeller shaft speeds up, the planet carrier slows down and less engine-produced energy is absorbed by the generator.

In urban operation the engine runs at constant speed and power. Its throttle is preset and its speed is controlled by increasing or decreasing the alternator's load to reflect a balancing torque back on the engine shaft.

FIGURE 3.1
EMT HYBRID SYSTEM IN URBAN TRAFFIC MODE

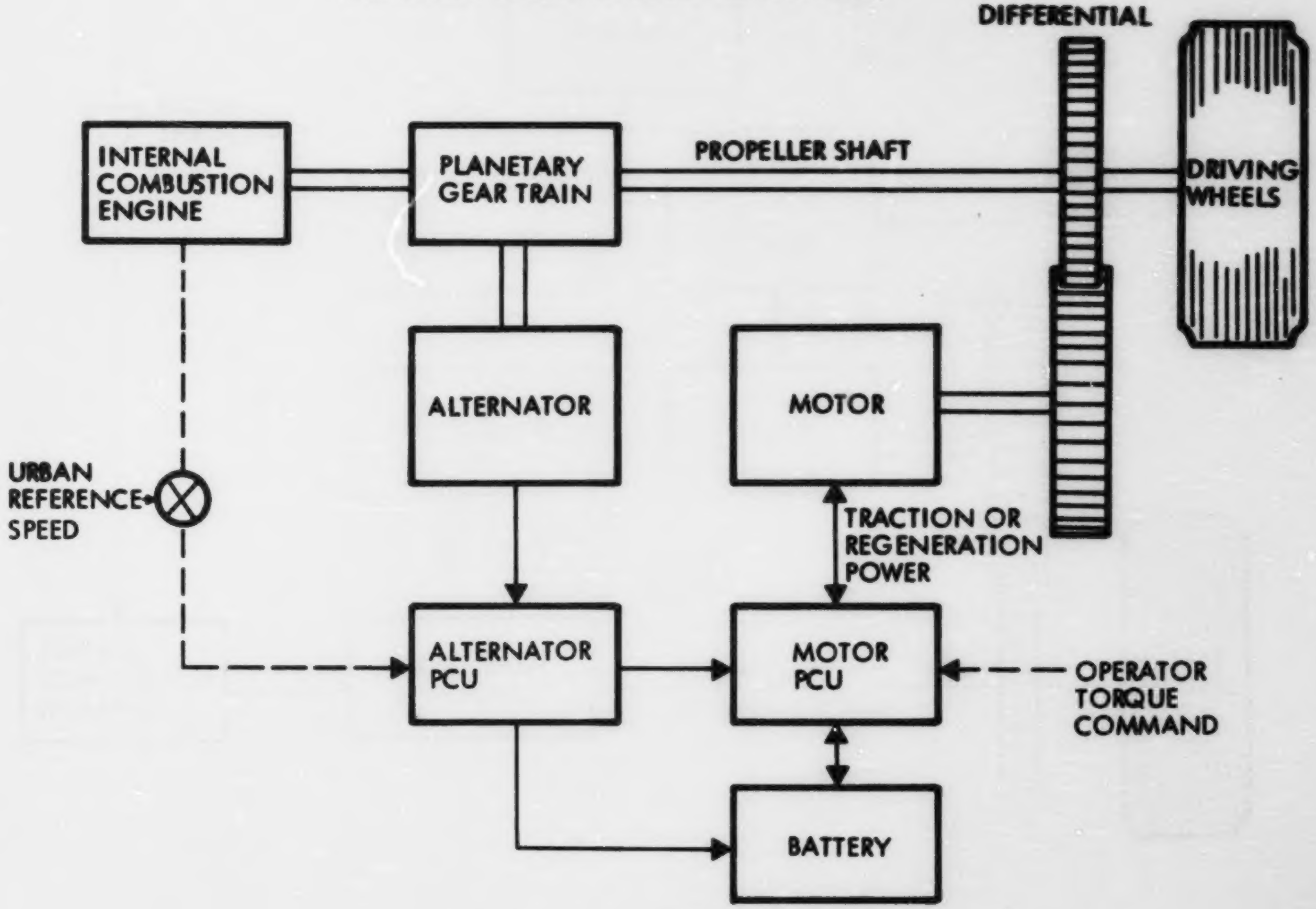
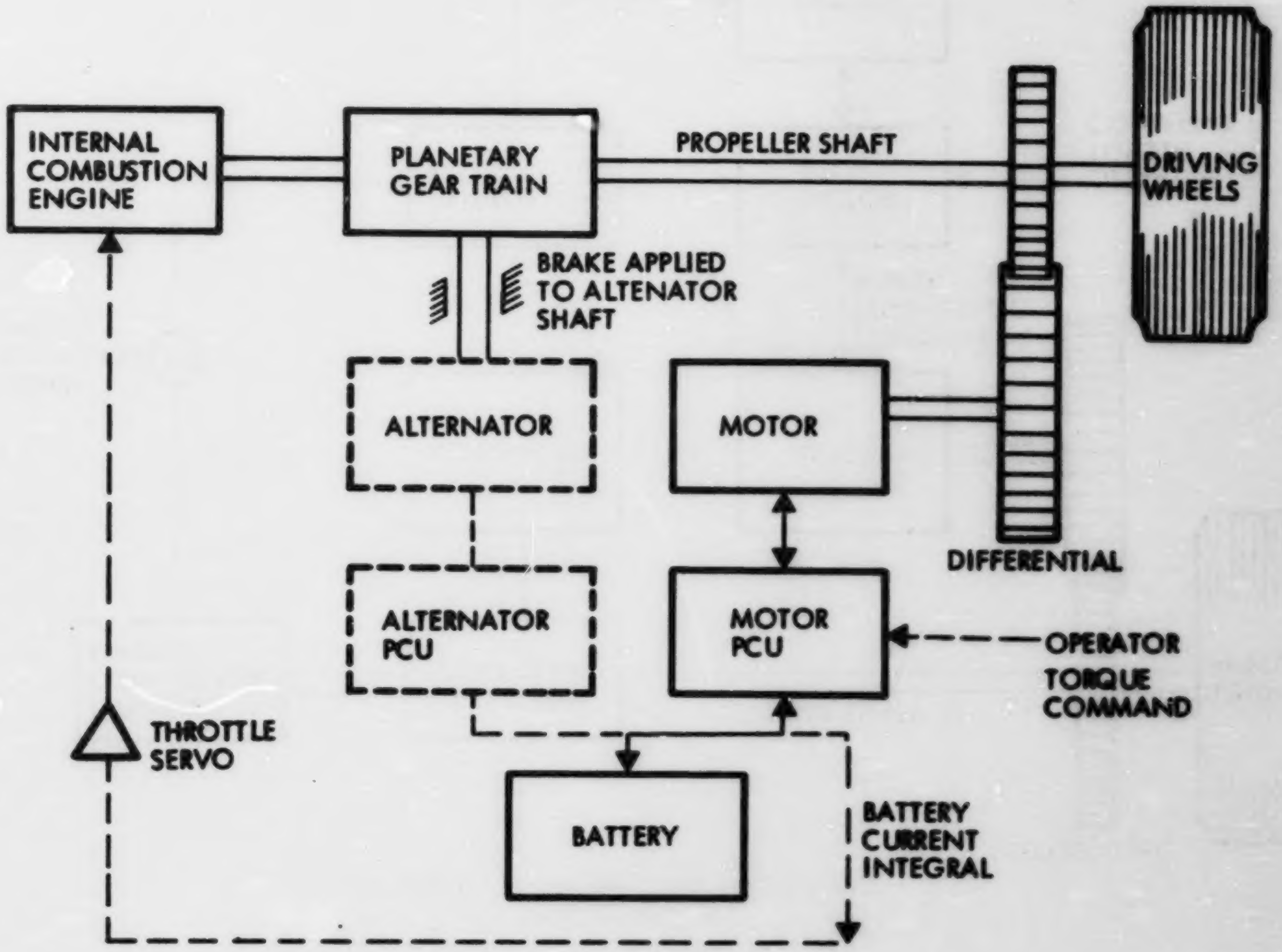

DIFFERENTIAL
INTERNAL COMBUSTION ENGINE
PLANETARY GEAR TRAIN
PROPELLER SHAFT
DRIVING WHEELS
ALTERNATOR
MOTOR
URBAN REFERENCE SPEED
TRACTION OR REGENERATION POWER
ALTERNATOR PCU
MOTOR PCU
OPERATOR TORQUE COMMAND
BATTERY

FIGURE 3.2
EMT HYBRID SYSTEM IN HIGHWAY TRAFFIC MODE


INTERNAL COMBUSTION ENGINE
PLANETARY GEAR TRAIN
PROPELLER SHAFT
DRIVING WHEELS
BRAKE APPLIED TO ALTENATOR SHAFT
ALTERNATOR
MOTOR
DIFFERENTIAL
ALTERNATOR PCU
MOTOR PCU
OPERATOR TORQUE COMMAND
THROTTLE SERVO
BATTERY
BATTERY CURRENT INTEGRAL

The torque on the propeller shaft is directly related to the engine's torque and planetary gear ratio. Since they are both constant in urban operation, the propeller shaft torque is essentially constant in that mode. The driving wheel torque is therefore must be controlled by a traction motor which is capable of adding torque to (motor operation) or subtracting torque from (generator operation) the propeller shaft.

PCUs are provided between the alternator and battery bus in order that the alternator's output voltage can be boosted to battery voltage at constant armature current. (Alternator field flux is maintained constant at saturation.) A bi-directional PCU between battery bus and motor receives operator commands in terms of desired motor torque magnitude and sign. For motoring, the PCU acts as a chopper as in the PCU for the full voltage series system. For generation, it acts as a boost PCU as in the series system with an alternator PCU.

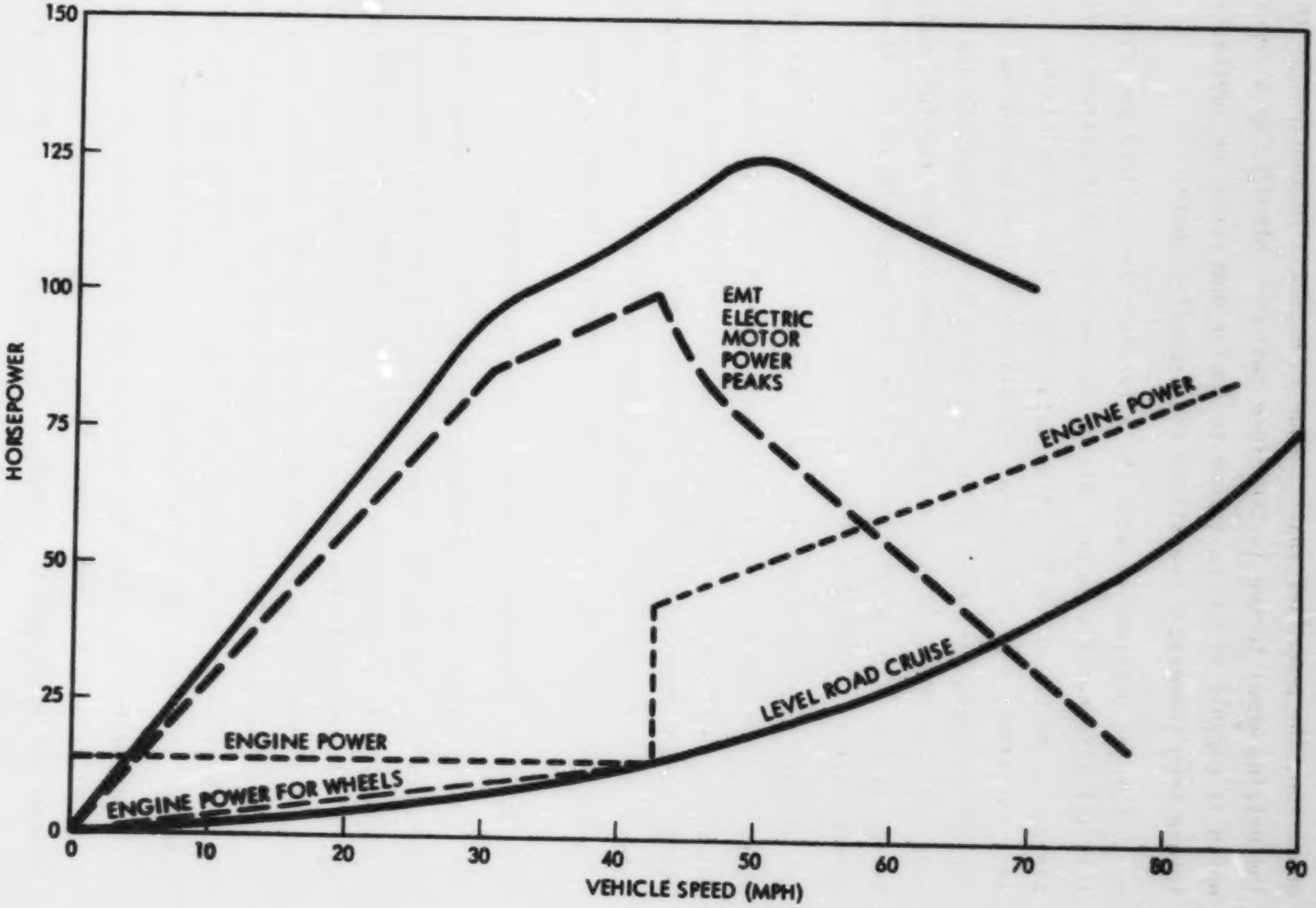
During highway operation, the planet carrier and the alternator are locked out and the engine speed increases linearly with road speed. The propeller shaft feels an engine torque proportional to the developed torque of the throttled engine. The motor/PCU continues to operate the same as in the urban mode. Engine throttle levels are slowly changed by a battery feedback loop as described in the full voltage system.

3.2 Specification of Parallel System Components

Previous studies showed that the continuous power rating of the traction motor for the EMT could be less than one-half required for 85 mph cruise. Figure 3.3 shows how the EMT's peak motor power varies with vehicle speed. In contrast with the series system, peak motor power of the parallel system reaches a maximum around 42.5 mph and then falls rapidly to zero at 85 mph. On the other hand, since the motor must deliver the power for vehicle acceleration, the motor will have to operate at perhaps two to three times rated torque at one-fourth its rated speed.

One method suggested for reducing the motor torque and improving motor efficiency at lower speeds is to use a multi-step gear ratio between the motor and the wheels. Thus, at any road speed and power the

FIGURE 3.3
POWER LEVELS OF EMT HYBRID SYSTEMS MOTOR AND ENGINE



motor will be able to turn at a higher rpm and lower torque and reduce ohmic losses and PCU current requirements.

Table 3.1 presents a comparison of efficiencies of the motor at various peak load conditions with and without gearing. The gear ratio schedule between the motor and differential is assumed to be:

2:1 from 0 to 42.5 mph
1.5:1 from 42.5 to 55 mph
1:1 from 55 to 85 mph

The characteristics of the motor on which these calculations are based can be found in Appendix D.

TABLE 3.1
EFFECT OF GEAR SHIFTING ON EMT TRACTION MOTOR

Road Speed (mph)	Road Power (hp)	Torque P.U.	Current (amperes)	Motor Voltage	Motor RPM	Motor Eff.	With Gear Shift				
							Torque P.U.	Current (amperes)	Motor Voltage	Motor RPM	Motor Eff.
30	95	10	900	113	2500	70	5	500	174	5100	81
42.5*	114						4.2	435	224	7200	87
42.5	114						5.6	530	197	5400	82
50	125	7.9	720	166	4250	78					
55.0*	120						4.5	460	223	7000	87
55.0	120						6.75	625	182	4650	79
70.0	103	4.8	455	200	5950	84	4.8	455	200	5950	84
85.0	27	1	130	172	7200	89	1	130	172	7200	89

*Values immediately before gear shift

The greatest improvement in motor efficiency takes place at low vehicle speeds where gearing affects motor torque requirement the most. While the series system's motor efficiency is also improved by using a variable ratio gear train, low speed improvement is not as great as in the EMT system since the series machine is rated at a higher nominal torque level and thus can operate more efficiently at low speeds.

A secondary benefit of gearing is that is may allow some relaxation of battery requirements in terms of power density. Improved machine efficiency means less power demand on the battery for acceleration and for similar motor loads a lighter weight or low power density battery could be used.

The alternator for the EMT system operates under unique circumstances. The alternator's speed varies over a 10:1 speed range between vehicle speeds of 0 to 42.5 mph. Since its shaft torque is essentially constant over that range, its input power varies by a factor of ten. In order to utilize the machine's field as fully as possible, the machine must be run with a saturated field under all cases. The resulting 10:1 variation in alternator voltage is handled by boost power conditioning between the alternator and battery. The preliminary rating of the alternator was based on it being capable of absorbing the full output of the engine for extended periods (car at rest). Thus, assuming a nominal 15 hp engine output in urban operation and a 90% efficiency planetary gear system, the alternator was rated at 10 kw input/12,000 rpm.

The planetary gear efficiency is dependent on the detailed design of the gear system and its lubrication. The planetary gear box designed for the EMT dynamometer demonstration combined planetary elements of a conventional automatic transmission with spur gears within a completely oil-flooded housing. With the addition of extra gears to adjust the planetary ratios to the various input/output shafts, the average efficiency of the gear box computed as the sum of the alternator and propeller shaft outputs divided by the engine input was around 75%. Various mechanical design handbooks indicate gear efficiencies typically >95%. In order to reflect the variability of design, two planetary gear system efficiencies were chosen, 80 and 90%, and the effect of gear efficiency on overall system efficiency was treated parametrically.

Other gearing efficiencies were estimated from handbook values. Generally, gear efficiencies were taken as a decreasing function gear or shaft speeds to account for windage and lubrication losses which would tend to increase non-linearity with speed.

The power conditioning units were characterized in terms of their current and KVA capabilities. Detailed designs were made to identify:

- appropriate SCR and rectifier elements
- commutation capacitors, inductors and reactors
- fusing
- relays
- electronic logic elements

Two designs for the motor PCU were developed. One had a current handling capacity of 900 amperes, the other 600 amperes. The lower current design was used where variable gearing was assumed; in these cases, the gearing would reduce motor and hence PCU current and commutation requirements. Complete descriptions of the PCUs are to be found in Appendix E.

4.0 CHARACTERIZATION OF HYBRID VEHICLE BATTERIES

The lead-acid batteries were characterized in terms of their internal impedance. A review of battery charge/discharge characteristics(2) as well as studies from the hybrid vehicle lead-acid development program(3) indicated battery impedance was a function of battery design and charge state.

Experience with the EMT and previous computer analyses(1,2) showed that the variation of the battery charge state during LA-4 operation was so small that charge state effects on impedance could be neglected and full charge impedance was taken as the battery variable. Measurements taken during the lead-acid development program showed that a 240 VDC battery (120 cells) having a 75-second power density of over 150 watts/pound would have an impedance of 86×10^{-3} ohms. Degraded battery conditions were modeled by assuming impedances of 170×10^{-3} and 240×10^{-3} ohms, reflecting 50% and 67% losses in active material area.

A charge model for the battery was not incorporated as part of the program. Previous analyses had shown that the energy associated with gasing during charge would be very small relative to the charge or discharge power levels. Experiments on the EMT showed the water losses from standard SLI batteries operating on the LA-4 driving cycle have typically been very small, also suggesting a low energy loss due to gasing.

5.0 MODELING AND SIMULATION OF HYBRID VEHICLES

5.1 Instantaneous Values of Component Performance of Series and Parallel Hybrid Power Trains

Appendix F presents the detailed computer program models and simulation procedures for analyzing both the instantaneous and LA-4 performance of the full voltage series and parallel hybrid systems. The instantaneous values, i.e., the values of power train component operation at matrix values of vehicle acceleration and speed are to be found in Appendix G.

The computer print-out is divided into those quantities which are velocity and acceleration dependent--motor power levels, battery voltages and currents, PCU efficiencies, etc., and those quantities which are vehicle speed dependent only, such as engine power level.

Those places in the computer listing where the motor PCU chopper duty cycle, α, equals 1.0, are points where, for the particular vehicle parameters of that computation, the battery voltage either sank too low to provide the motor's terminal voltage requirement or the voltage of the motor was too low relative to the battery voltage for the motor PCU acting as a boost PCU to charge the battery.

5.2 LA-4 Performance of Series and Parallel Hybrid Power Trains

The performance of series and parallel hybrids was evaluated for urban operation as defined by the LA-4 route. The velocity-time profiles used as inputs were gathered from fifth wheel data of actual cars driving a specific route in Los Angeles traffic during morning hours. The route is such that it combines congested, freeway & boulevard traffic in a manner representative of L.A. driving. A composite of LA-4 velocity-time data forms basis for the 1972 Federal driving cycle; however, the LA-4 route is longer, requiring about 30 minutes and covering about 10 miles. A total of 14 hours of vehicle operation, representing about 52,000, one-second events had been previously reduced for computer input.

The performance of simulated vehicles operating on the LA-4 driving profile was computed by multiplying the instantaneous component operating values by the probability of occurrence in the LA-4 velocity-acceleration matrix. Appendix F describes the procedure more fully and also indicates how component driving cycle averages and RMS values were computed.

Figures 5.1, 5.2, 5.3, 5.4, and 5.5 show block diagrams of the full voltage series system along with the average efficiencies and input/output levels which result from operation on the LA-4 cycle. Figures 5.6, 5.7, 5.8, 5.9, and 5.10 present similar information for the parallel system.

The numbers associated with each block in the diagrams represent the average efficiency of the component during LA-4 operation. The battery losses are shown as a separate item; in each of the runs the battery charge state did not change from run start to finish. The arrows and power levels show the power flow direction and average values at selected points of the system. Average power levels at other points can be found by multiplication of the efficiencies within the blocks. In all the calculations vehicle accessory loads were neglected.

5.3 Effect of Series and Parallel System Parameters on Overall System Efficiency

The important operating parameters of the two hybrid systems were varied to determine their effect on system performance. The parameters which were varied were the engine input power in the urban mode, battery impedance, the efficiencies of gear 1, gear 2 and the planetary gearing. The effects of the introduction of a variable transmission ratio between the motor output shaft and the differential, and the possible benefits of vehicle kinetic energy regeneration were also studied. A single test run was also made on the series system model operating without the engine to simulate the performance of an all-electric vehicle.

FIGURE 5.1

FULL VOLTAGE SERIES SYSTEM ON LA-4 MISSION WITH
VARIABLE GEARING AND REGENERATION
RUN IA

$\eta_{SYS} = 55.2\%$

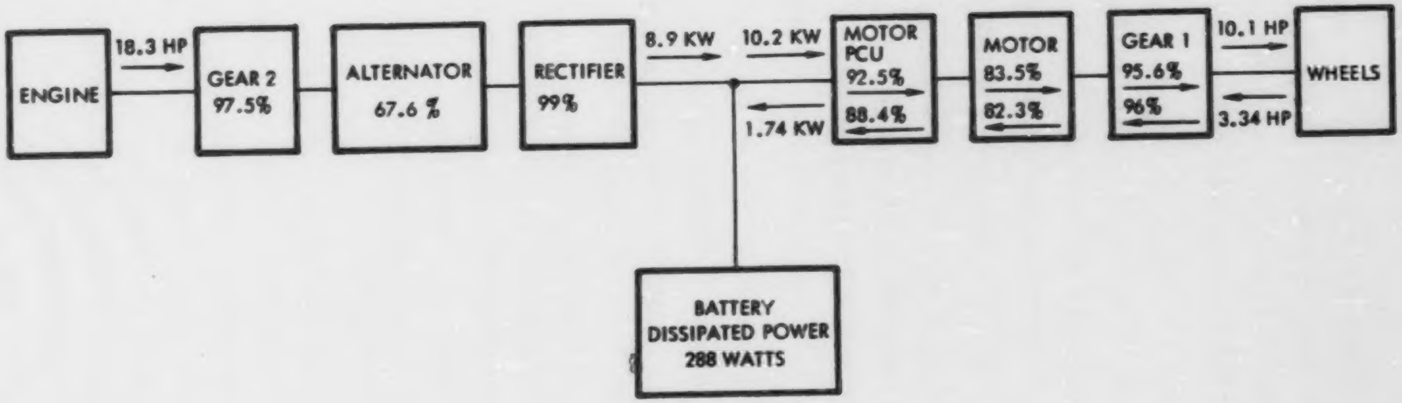

ENGINE
18.3 HP
GEAR 2
97.5%
ALTERNATOR
67.6 %
RECTIFIER
99%
8.9 KW
10.2 KW
1.74 KW
MOTOR PCU
92.5%
88.4%
MOTOR
83.5%
82.3%
GEAR 1
95.6%
96%
10.1 HP
3.34 HP
WHEELS
BATTERY
DISSIPATED POWER
288 WATTS

FIGURE 5.2

FULL VOLTAGE SERIES SYSTEM ON LA-4 MISSION WITH
VARIABLE GEARING AND REGENERATION
RUN GA

$\eta_{SYS} = 52.0\%$

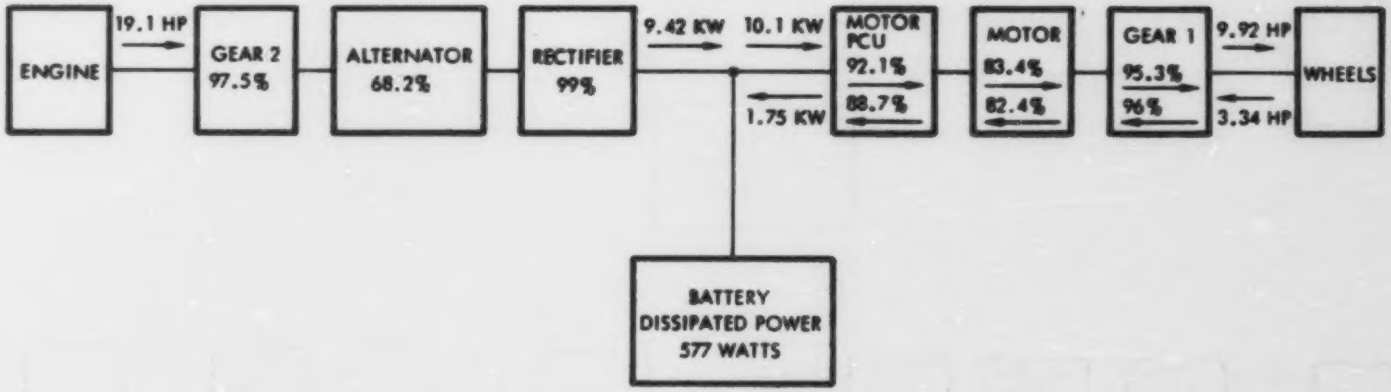

ENGINE
19.1 HP
GEAR 2
97.5%
ALTERNATOR
68.2%
RECTIFIER
99%
9.42 KW
10.1 KW
1.75 KW
MOTOR
PCU
92.1%
88.7%
MOTOR
83.4%
82.4%
GEAR 1
95.3%
96%
9.92 HP
3.34 HP
WHEELS
BATTERY
DISSIPATED POWER
577 WATTS

FIGURE 5.3

FULL VOLTAGE SERIES SYSTEM ON LA-4 MISSION WITHOUT
VARIABLE GEARING, WITH REGENERATION
RUN CA

$\eta_{SYS} = 47.9\%$

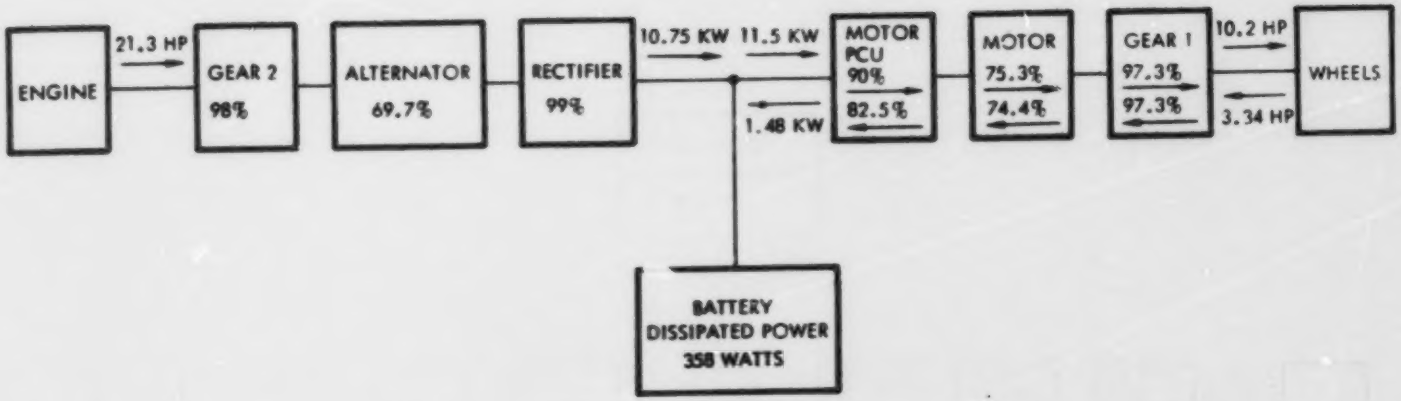

ENGINE
21.3 HP
GEAR 2
98%
ALTERNATOR
69.7%
RECTIFIER
99%
10.75 KW
11.5 KW
1.48 KW
MOTOR
PCU
90%
82.5%
MOTOR
75.3%
74.4%
GEAR 1
97.3%
97.3%
10.2 HP
3.34 HP
WHEELS
BATTERY
DISSIPATED POWER
358 WATTS

FIGURE 5.4

FULL VOLTAGE SERIES SYSTEM ON LA-4 MISSION WITH
VARIABLE GEARING, WITHOUT REGENERATION
RUN BBA

$\eta_{SYS} = 46.4\%$

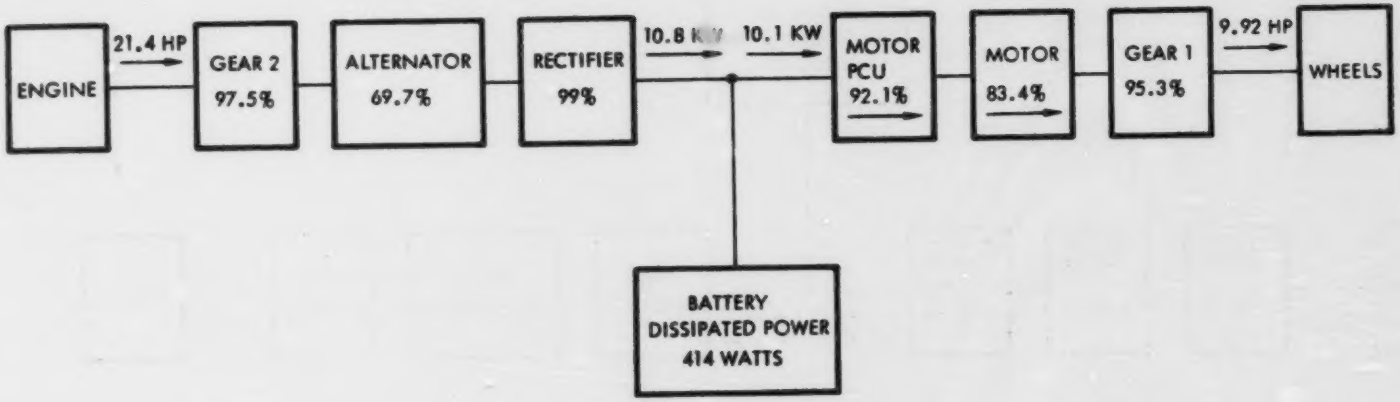

ENGINE
21.4 HP
GEAR 2
97.5%
ALTERNATOR
69.7%
RECTIFIER
99%
10.8 KW
10.1 KW
MOTOR
PCU
92.1%
MOTOR
83.4%
GEAR 1
95.3%
9.92 HP
WHEELS
BATTERY
DISSIPATED POWER
414 WATTS

FIGURE 5.5

FULL VOLTAGE SERIES SYSTEM ON LA-4 MISSION WITHOUT
VARIABLE GEARING OR REGENERATION
RUN AAA

$\eta_{SYS} = 42.9\%$

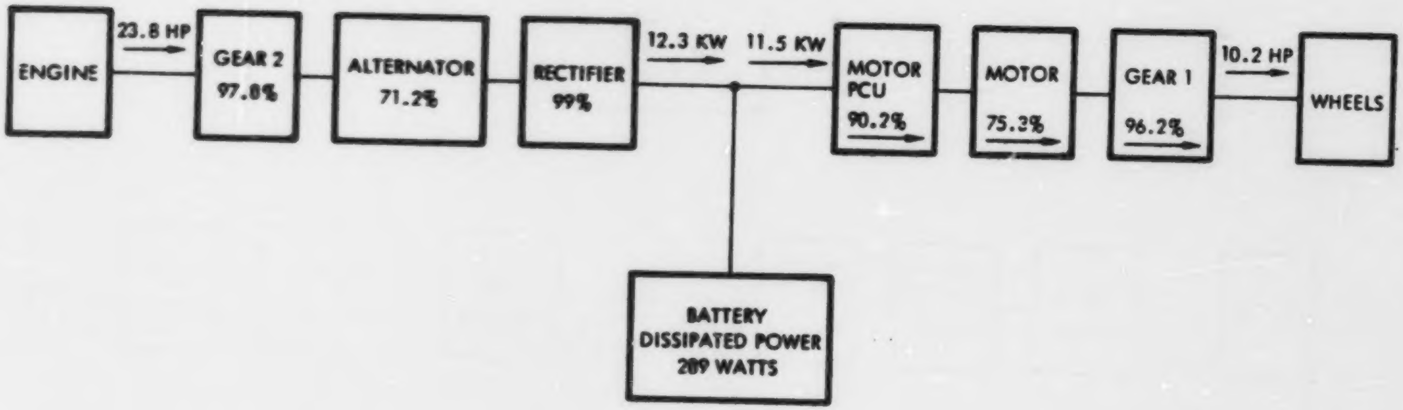

ENGINE
23.8 HP
GEAR 2
97.8%
ALTERNATOR
71.2%
RECTIFIER
99%
12.3 KW
11.5 KW
MOTOR
PCU
90.2%
MOTOR
75.3%
GEAR 1
96.2%
10.2 HP
WHEELS
BATTERY
DISSIPATED POWER
289 WATTS

FIGURE 5.6

EMT SYSTEM ON LA-4 MISSION WITH VARIABLE GEARING AND REGENERATION
RUN TAA
$\eta_{SYS} = 75.7\%$

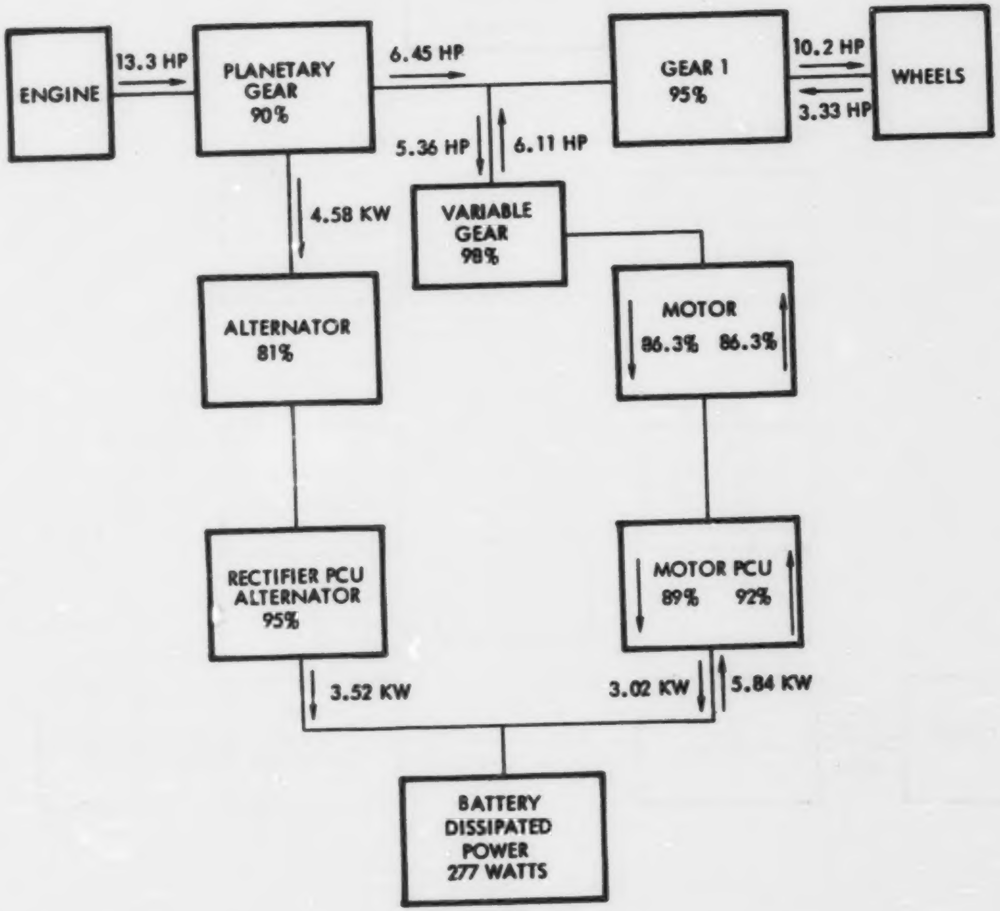

ENGINE
13.3 HP
PLANETARY GEAR 90%
6.45 HP
GEAR 1 95%
10.2 HP
3.33 HP
WHEELS
5.36 HP
6.11 HP
VARIABLE GEAR 98%
4.58 KW
ALTERNATOR 81%
MOTOR 86.3% 86.3%
RECTIFIER PCU ALTERNATOR 95%
MOTOR PCU 89% 92%
3.52 KW
3.02 KW
5.84 KW
BATTERY DISSIPATED POWER 277 WATTS

FIGURE 5.7

EMT SYSTEM ON LA-4 MISSION WITH VARIABLE GEARING AND REGENERATION

RUN XA

$\eta_{SYS} = 66.6\%$

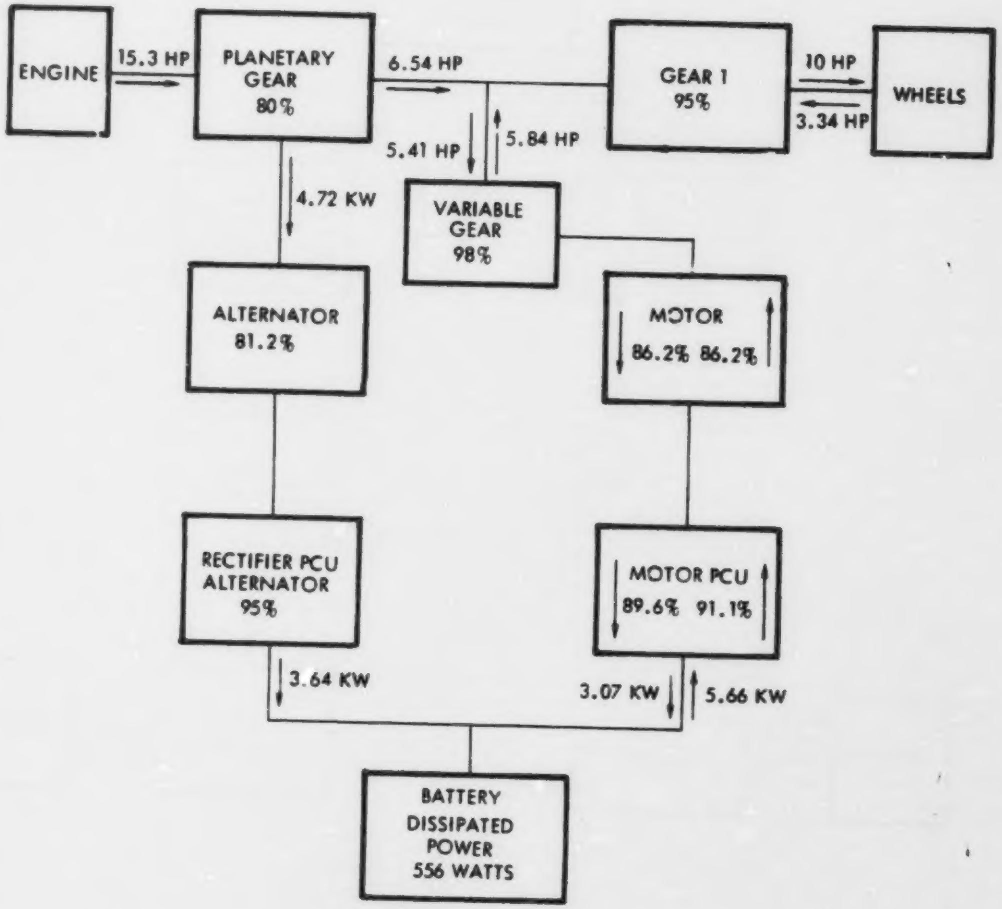

ENGINE
15.3 HP
PLANETARY GEAR 80%
6.54 HP
GEAR 1 95%
10 HP
3.34 HP
WHEELS
5.41 HP
5.84 HP
4.72 KW
VARIABLE GEAR 98%
ALTERNATOR 81.2%
MOTOR
86.2% 86.2%
RECTIFIER PCU ALTERNATOR 95%
MOTOR PCU
89.6% 91.1%
3.64 KW
3.07 KW
5.66 KW
BATTERY DISSIPATED POWER 556 WATTS

FIGURE 5.8

EMT SYSTEM ON LA-4 MISSION WITHOUT VARIABLE GEARING, WITH REGENERATION

RUN RA

$\eta_{SYS} = 61.7\%$

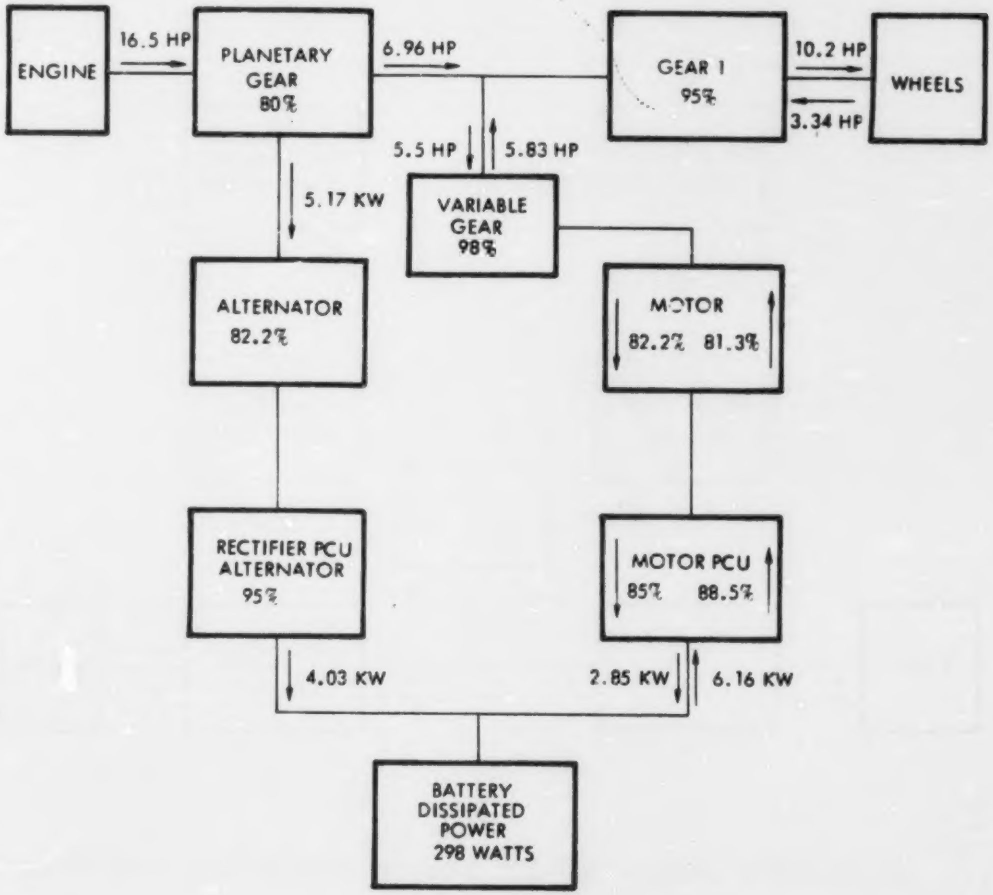

ENGINE
16.5 HP
PLANETARY GEAR 80%
6.96 HP
GEAR 1 95%
10.2 HP
3.34 HP
WHEELS
5.5 HP
5.83 HP
VARIABLE GEAR 98%
5.17 KW
ALTERNATOR 82.2%
MOTOR 82.2% 81.3%
RECTIFIER PCU ALTERNATOR 95%
MOTOR PCU 85% 88.5%
4.03 KW
2.85 KW
6.16 KW
BATTERY DISSIPATED POWER 298 WATTS

FIGURE 5.9

EMT SYSTEM ON LA-4 MISSION WITH VARIABLE GEARING, WITHOUT REGENERATION
RUN LLA
$\eta_{SYS} = 54.0\%$

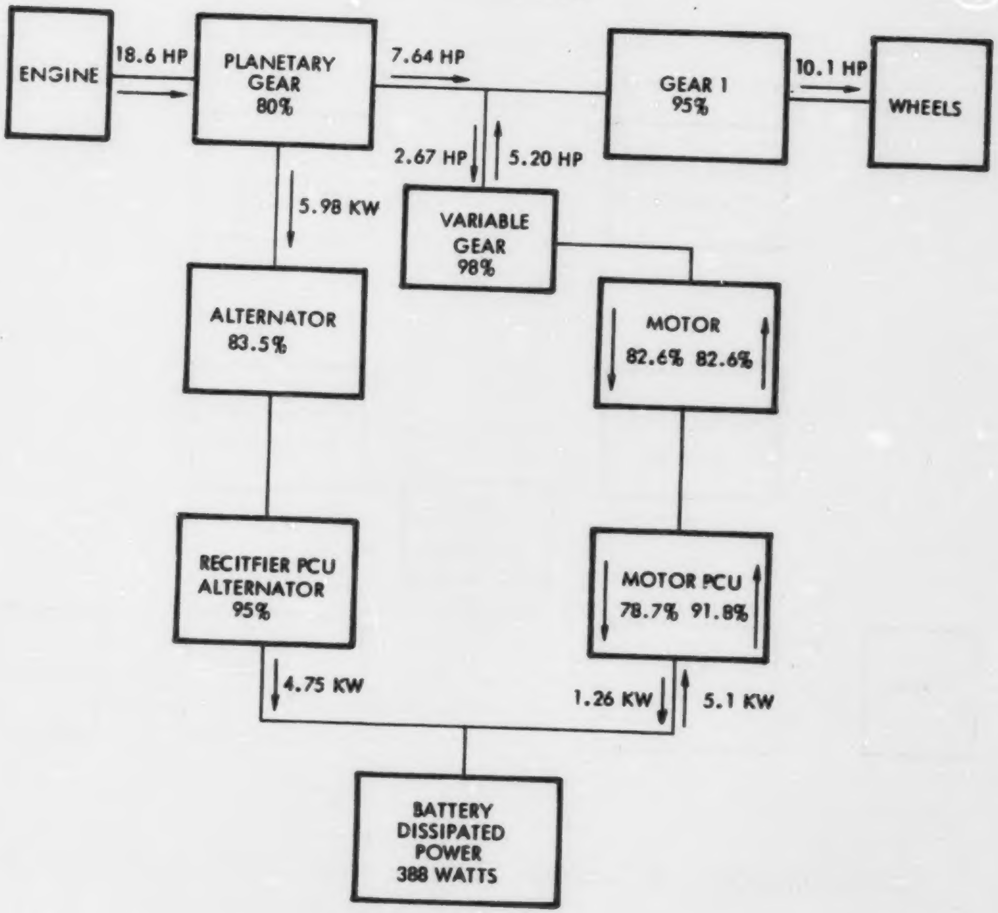
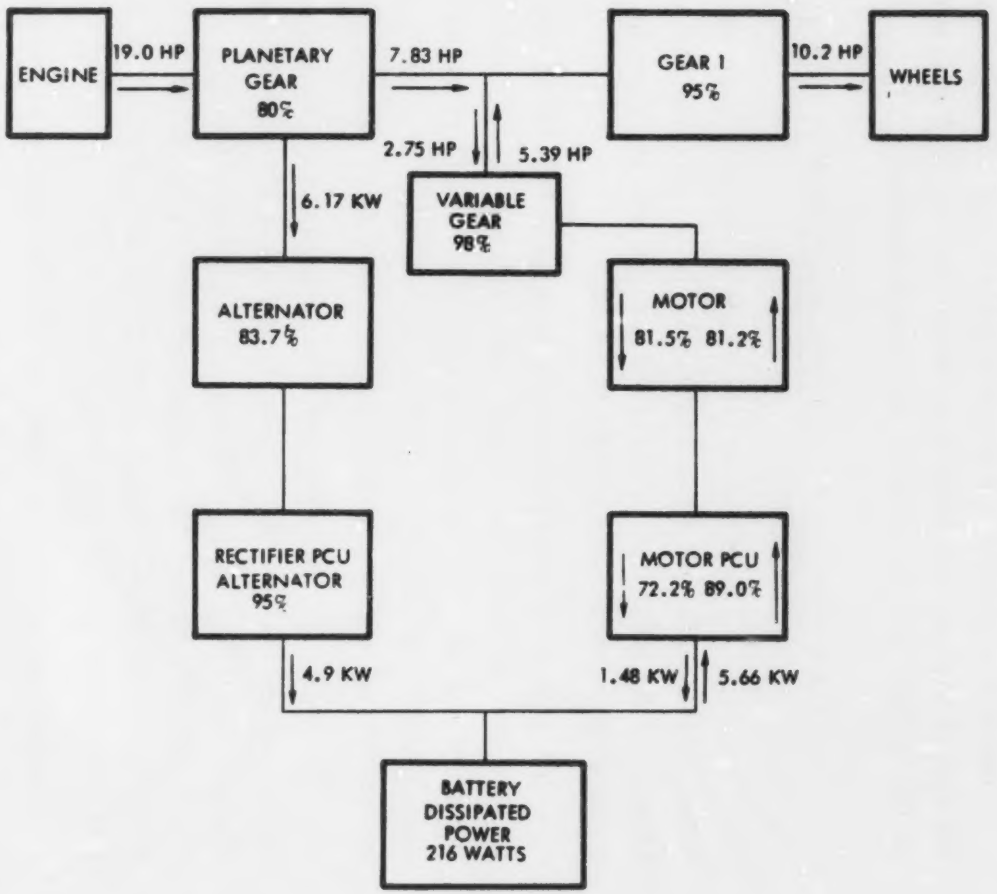

ENGINE
18.6 HP
PLANETARY GEAR 80%
7.64 HP
GEAR 1 95%
10.1 HP
WHEELS
2.67 HP
5.20 HP
5.98 KW
VARIABLE GEAR 98%
ALTERNATOR 83.5%
MOTOR 82.6% 82.6%
RECITFIER PCU ALTERNATOR 95%
MOTOR PCU 78.7% 91.8%
4.75 KW
1.26 KW
5.1 KW
BATTERY DISSIPATED POWER 388 WATTS

FIGURE 5.10

EMT SYSTEM ON LA-4 MISSION WITHOUT VARIABLE GEARING OR REGENERATION
RUN JJA
$\eta_{SYS} = 53.6\%$


ENGINE
19.0 HP
PLANETARY GEAR 80%
7.83 HP
GEAR I 95%
10.2 HP
WHEELS
2.75 HP
5.39 HP
6.17 KW
VARIABLE GEAR 98%
ALTERNATOR 83.7%
MOTOR 81.5% 81.2%
RECTIFIER PCU ALTERNATOR 95%
MOTOR PCU 72.2% 89.0%
4.9 KW
1.48 KW
5.66 KW
BATTERY DISSIPATED POWER 216 WATTS

Tables 5.1 and 5.2 present listings of the combinations of parameters and operating modes of the more meaningful simulation runs. In the initial runs it was impossible to assign appropriate parameter values such that during LA-4 driving the battery charge state would be constant. Thus, many of the runs shown here are part of a learning procedure by which we were able to define the conditions for constant charge state.

Tables 5.3 through 5.6 present the average and selected RMS values of the hybrid systems and major components for the LA-4 mission. Definitions of the symbols can be found in the nomenclature.

5.3.1 Effect of System Parameters on Full Voltage Series System Performance

The effect of inserting a variable gear ratio between the motor output shaft and the differential is to increase the series system's efficiency by about 15%. Comparing runs CA and IA shows that system efficiency increases from 47.9% to 55.0%.

The effect of doubling battery impedance from 86 to 172 milliohms in a fixed gear ratio series system is to decrease system efficiency as shown in runs K and CA. System efficiency falls from 47.9% to 44.0%. In a geared system the effect is similar as indicated in runs IA and GA where the respective efficiency decrease is from 55% to 52%.

The effect of degrading the efficiency of the gearing between the engine and the alternator (g_2) is in direct proportion to the efficiency change. Comparing runs Z, CA and K shows that a decrease of η_{g2} from .98-.95 to .90-.87 reduces the system efficiency from 47.9% to 44.2%, nearly a 10% reduction in efficiency. The effect of changing the differential gear efficiency (g_1) is similar.

Comparison of runs CA, AAA, GA and BBA shows that regeneration affects overall efficiency. Without regeneration, the series hybrid system efficiency loses about 10 percentage points.

TABLE 5.1

LIST OF INPUT PARAMETER VARIATIONS FOR THE SERIES SYSTEM COMPUTATIONS

Run Designation	P_{IC} (hp)	Battery Resistance ($\times 10^3 \Omega$) R_B	η_{g1}	η_{g2}	Variable Gearing	Regeneration
C	20.0	86	98-95	98-95	no	yes
D	17.5	86	97-94	98-95	yes	yes
F	17.5	86	98-95	98-95	no	yes
G	20.0	172	97-94	98-95	yes	yes
H	20.0	240	97-94	98-95	yes	yes
I	17.5	86	97-94	98-95	yes	yes
J	17.5	86	90-87	98-95	yes	yes
K	20.0	172	98-95	98-95	no	yes
Z	20.0	86	98-95	90-87	no	yes
CA	19.4	86	98-95	98-95	no	yes
GA	17	172	97-94	98-95	yes	yes
AA	20	86	98-95	98-95	no	no
AAA	22.2	86	98-95	98-95	no	no
BB	20	172	97-94	98-95	yes	no
BBA	19.5	172	97-94	98-95	yes	no
IA	16	86	97-94	98-95	yes	yes

TABLE 5.2

LIST OF INPUT PARAMETER VARIATIONS FOR THE PARALLEL SYSTEM COMPUTATIONS

Run Designation	P_{IC} (hp)	Battery Resistance ($\times10^{3}\Omega$) R_B	η_{go}	η_{gl}	Step Down Gearing	Regeneration
R	15	86	80	97-94	no	yes
RA	14.9	86	80	97-94	no	yes
X	15	172	80	97-94	yes	yes
P	15	86	90	97-94	no	yes
Q	13	86	90	97-94	no	yes
S	15	172	90	97-94	no	yes
T	13	86	90	97-94	yes	yes
TA	11	86	90	97-94	yes	yes
TAA	11.75	86	90	97-94	yes	yes
U	15	86	80	97-94	yes	yes
V	13	86	80	97-94	yes	yes
W	13	172	80	97-94	yes	yes
Y	13	86	90	98-87	yes	yes
CC	15	86	80	97-94	no	no*
CCA	19.7	86	80	97-94	no	no*
EE	15	172	80	97-94	yes	no*
EEA	18.6	172	80	97-94	yes	no*
XA	13.6	172	80	97-94	yes	yes
JJ	15	86	80	97-94	no	engine [illegible] only**
JJA	17.8	86	80	97-94	no	engine [illegible] only**
KK	15	172	80	97-94	yes	engine power only**
KKA	17	172	80	97-94	yes	engine power only**
LLA	17.25	172	80	97-94	yes	engine power only**

* Traction motor not operated as generator

** Traction motor operated as generator but absorbs engine power contribution to propeller shaft only

TABLE 5.3
PERFORMANCE OF FULL VOLTAGE SERIES SYSTEM COMPONENTS ON LA-4 MISSION

Run	D	F	H	K	Z
Urban Engine Power, hp	17.5	17.5	20	20	20
Battery Resistance, $10^3 \Omega$	86	86	240	172	86
Motor-Wheel Gear Ratio	variable	1:1	variable	1:1	1:1
η_{g1}	.97-.94	.98-.95	.97-.94	.98-.95	.98-.95
η_{g2}	.98-.95	.98-.95	.98-.95	.98-.95	.90-.87
$\overline{P}_R$, hp	6.9123+00	6.9119+00	6.9408+00	6.9127+00	6.9119+00
in drive	1.4537+01	1.4536+01	1.4622+01	1.4538+01	1.4536+01
in regen	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01
$\hat{P}_{Mo}$	2.0192+01	2.0066+01	2.0234+01	2.0193+01	2.0066+01
$\overline{P}_{Mo}$, hp	1.3097+01	1.3829+01	1.3964+01	1.3907+01	1.3829+01
in drive	1.5166+01	1.5008+01	1.5255+01	1.5167+01	1.5008+01
in regen	-1.0894+01	-1.1007+01	-1.0894+01	-1.0894+01	-1.1007+01
$\overline{P}_{Mi}$, kw	1.1515+01	1.2277+01	1.1562+01	1.2379+01	1.2277+01
in drive	1.3531+01	1.4855+01	1.3611+01	1.5024+01	1.4855+01
in regen	-6.6917+00	-6.1128+00	-6.6917+00	-6.054 +00	-6.1128+00
$\hat{I}_M$	4.6843+01	8.9723+01	4.6939+01	9.009 +01	8.9723+01
$\overline{P}_{PCU}$	1.2177+01	1.3089+01	1.2181+01	1.3343+01	1.3089+01
in drive	1.486 +01	1.6451+01	1.48 +01	1.6812+01	1.6451+01
in regen	-5.7594+00	-5.0481+00	-5.952 +00	-5.0494+00	-5.0481+00
$\overline{P}_B$	-9.583 -01	3.7428-01	-2.4571+00	-7.0269-01	1.4607-01
charge	-9.848 +00	-8.6108+00	-1.0361+01	-9.6202+00	-9.5777+00
discharge	9.9857+00	1.2832+01	9.4908+00	1.2451+01	1.1655+01
$\overline{P}_{IC}$, hp	1.9634+01	1.9633+01	2.1966+01	2.1877+01	2.1875+01
$\overline{P}_{Ai}$	1.4325+01	1.4324+01	1.6029+01	1.5964+01	1.4657+01
$\overline{P}_{Ao}$	9.8379+00	9.8373+00	1.1226+01	1.118 +01	1.0067+01
$\hat{I}_M$	1.5767+02	2.5506+02	1.58 +02	2.5592+02	2.5506+02
$\overline{I}_M$	1.3763+02	2.0691+02	1.3819+02	2.0757+02	2.0691+02
in drive	1.394 +02	2.0676+02	1.4021+02	2.0832+02	2.0676+02
in regen	-1.3339+02	-2.0727+02	-1.3339+02	-2.0576+02	-2.0727+02
$\hat{I}_{PCU}$	7.3875+01	8.1607+01	7.5375+01	8.8721+01	8.167 +01
$\overline{I}_{PCU}$	5.1595+01	5.587 +01	5.1721+01	5.8591+01	5.59 +01
in drive	6.3479+01	7.0715+01	6.3983+01	7.4847+01	7.0757+01
in regen	-2.3173+01	-2.0362+01	-2.2566+01	-1.9715+01	-2.0363+01
$\overline{I}_B$	-1.6845+00	4.161 +00	-6.3354+00	1.8099+00	3.2632+00
charge	-4.0103+01	-3.5097+01	-4.0573+01	-3.8385+01	-3.906 +01
discharge	4.5663+01	5.8597+01	4.7795+01	6.1224+01	5.3361+01
$\overline{I}_A$	3.8174+01	3.9615+01	4.4695+01	4.5109+01	3.8932+01
drive probability	0.70516	0.70518	0.70394	0.70514	0.70518
regen probability	0.29483	0.29481	0.29605H	0.29485	0.29481

Run	C	CA	G	GA	AA	AAA	BB	BBA	J	I	IA	All Electric
Urban Engine Power	20	19.4	20	17	20	22.2		19.5	17.5	17.5	16	0
Battery Resistance, $10^3\Omega$	86	86	172	172	86	86	172	172	86	86	86	86
Motor-Wheel Gear Ratio	1:1	1:1	variable	variable	1:1	:1	variable	variable	variable	variable	variable	variable
η_{g1}	.98-.95	.98-.95	.97-.94	.97-.94	.98-.95	.98-.95	.97-.94	.97-.94	.90-.87	.97-.94	.97-.94	.97-.94
η_{g2}	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95	.98-.95
$\bar{P}_p$, hp	6.9034+00	6.9034+00	6.6128+00	6.6128+00	6.9034+00	6.9034+00	6.6128+00	6.6128+00	6.7413+00	6.7907+00	6.7907+00	6.7268+00
in drive	1.4525+01	1.4525+01	1.4156+01	1.4156+01	1.4525+01	1.4525+01	1.4156+01	1.4156+01	1.432 +01	1.4381+01	1.4381+01	1.4301+01
in regen	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01	-1.1324+01
$\hat{P}_{Mo}$, hp	2.0039+01	2.0039+01	1.9493+01	1.9493+01	1.7872+01	1.7872+01	1.7297+01	1.7297+01	2.0786+01	1.99 +01	1.99 +01	1.976 +01
$\bar{P}_{Mo}$, hp	1.382 +01	1.382 +01	1.362 +01	1.362 +01	1.0575+01	1.0575+01	1.0394+01	1.0394+01	1.4338+01	1.3789+01	1.3789+01	1.3729+01
in drive	1.4997+01	1.4997+01	1.4766+01	1.4766+01	1.4997+01	1.4997+01	1.4766+01	1.4766+01	1.6115+01	1.5002+01	1.5002+01	1.4918+01
in regen	-1.1007+01	-1.1007+01	-1.0894+01	-1.0894+01	0. +00	0. +00	0. +00	0. +00	-1.0101+01	-1.0894+01	-1.0894+01	-1.0894+01
$\bar{P}_{Mi}$, kw	1.2271+01	1.2271+01	1.1278+01	1.1278+01	1.0468+01	1.0468+01	9.2974+00	9.2974+00	1.1924+01	1.1419+01	1.1419+01	1.1368+01
in drive	1.4845+01	1.4845+01	1.3207+01	1.3207+01	1.4845+01	1.4845+01	1.3207+01	1.3207+01	1.4336+01	1.3399+01	1.3399+01	1.3331+01
in regen	-6.1127+00	-6.1127+00	-6.6917+00	-6.6917+00	0. +00	0. +00	0. +00	0. +00	-6.1747+00	-6.6917+00	-6.6917+00	-6.6917+00
$\bar{\eta}_M$, drive	7.5328-01	7.5328-01	8.3371-01	8.3371-01	7.5328-01	7.5328-01	8.3371-01	8.3371-01	8.3824-01	8.349 -01	4.6666+01	4.6558+01
$\bar{\eta}_M$, regen	7.4468-01	7.4468-01	8.2369-01	8.2369-01	0. +00	0. +00	0. +00	0. +00	8.1969-01	8.2369-01	1.1947+01	1.1887+01
$\hat{P}_M$	8.9713+01	8.9713+01	4.6323+01	4.6323+01	7.4507+01	7.4507+01	3.9084+01	3.9084+01	4.8374+01	4.6666+01	1.4473+01	1.4388+01
$\bar{P}_{PCU}$	1.3083+01	1.3084+01	1.1853+01	1.185 +01	1.1595+01	1.1598+01	1.0096+01	1.0095+01	1.2472+01	1.1947+01	-5.9181+00	-5.926 +00
in drive	1.6443+01	1.6444+01	1.4342+01	1.4326+01	1.6443+01	1.6448+01	1.4342+01	1.4341+01	1.5432+01	1.4475+01	-4.6392-01	8.3838+00
in regen	-5.047 +00	-5.0465+00	-5.9365+00	-5.9397+00	0. +00	0. +00	0. +00	0. +00	-5.4183+00	-5.9172+00	-9.457[illegible]+00	-8.9839+00
$\bar{\eta}_{PCU}$, drive	9.0283-01	9.0277-01	9.2086-01	9.2123-01	9.0283-01	9.0257-01	9.2086-01	9.2091-00	9.2897-01	9.2572-01	1.01[illegible]5+01	1.259 +01
$\bar{\eta}_{PCU}$, regen	8.2566-01	8.2556-01	8.8714-01	8.8762-01	0. +00	0. +00	0. +00	0. +00	8.775 -01	8.8426-01	1.82[illegible] +01	0. +00
$\bar{P}_B$	-9.585 -01	-6.3562-01	-2.7011+00	-1.1019+00	5.2959-01	-6.7492-01	-9.4365-01	-6.7462-01	-4.5314-01	-1.2689+00	1.332 +01	0. +00
charge	-9.0848+00	-9.5453+00	-1.025 +01	-9.6383+00	-6.7427+00	-7.9065+00	-7.4151+00	-7.8259+00	-9.6867+00	-9.6675+00	9.006 +00	0. +00
discharge	1.3202+01	1.1871+01	9.6094+00	9.8358+00	1.3202+01	1.2053+01	9.6094+00	8.6644+00	1.0587+01	1.0105+01	1.5728+02	1.5704+02
$\bar{P}_{IC}$	2.1872+01	2.1335+01	2.1833+01	1.9137+01	2.1872+01	2.3845+01	2.1833+01	2.1384+01	1.9609+01	1.9607+01	1.3733+02	1.3717+02
$\bar{P}_{Ai}$	1.596 +01	1.5567+01	1.5932+01	1.3962+01	1.596 +01	1.7402+01	1.5932+01	1.5604+01	1.4306+01	1.4305+01	1.3899+02	1.3876+02
$\bar{P}_{Ao}$	1.1177+01	1.0852+01	1.1151+01	9.5311+00	1.1177+01	1.2397+01	1.1151+01	1.0879+01	9.8214+00	9.8204+00	-1.3339+02	-1.3339+02
$\bar{\eta}_A$	7.0032-01	6.971 -01	6.9991-01	6.8265-01	7.0032-01	7.1242-01	6.9991-01	6.972 -01	6.8649-01	6.8647-01	7.2332+01	7.3154+01
$\hat{I}_M$	2.5504+02	2.5504+02	1.5653+02	1.5653+02	2.1255+02	2.1255+02	1.3215+02	1.3215+02	1.6106+02	1.5728+02	5.0619+01	5.1211+01
$\bar{I}_M$	2.0689+02	2.0689+02	1.3683+02	1.3683+02	1.4578+02	1.4578+02	9.7347+01	9.7347+01	1.4001+02	1.3733+02	6.1845+01	6.2578+01
in drive	2.0673+02	2.0673+02	1.3828+02	1.3828+02	2.0673+02	2.0673+02	1.3828+02	1.3828+02	1.4503+02	1.3899+02	-2.3828+01	-2.412 +01
in regen	-2.0727+02	-2.0727+02	-1.3339+02	-1.3339+02	0. +00	0. +00	0. +00	0. +00	-1.2806+02	-1.3339+02	2.6159-01	3.6851+01
I_M, max	1.1475+03	1.1475+03	1.1589+03	1.1589+03	1.1475+03	1.1475+03	1.1589+03	1.1589+03	1.2467+03	1.1589+03	-3.851 +01	-3.6566+01
$\hat{I}_{PCU}$	8.1428+01	8.1385+01	7.2861+01	7.3217+01	7.9339+01	7.9135+01	6.9888+01	6.9933+01	7.6741+01	7.2255+01	4.5867+01	5.4633+01
$\bar{I}_{PCU}$	5.5788+01	5.5759+01	5.0764+01	5.1002+01	4.9792+01	4.9667+01	4.394 +01	4.3967+01	5.2985+01	5.0563+01	3.6047+01	0. +00
in drive	7.0611+01	7.0575+01	6.2419+01	6.2709+01	7.0611+01	7.0435+01	6.2419+01	6.2456+01	6.606 +01	6.178 +01	0.70341	0.70245
in regen	-2.0337+01	-2.0324+01	-2.3051+0[illegible]	-2.3163+01	0. +00	0. +00	0. +00	0. +00	-2.1821+01	-2.3795+01	0.29476	0.29476
$\bar{I}_B$	-1.2342+00	6.4593-02	-7.5855+00	-1.1245+00	4.6824+00	-2.1748-01	-9.452 -01	1.4359-01	5.1935-01	-2.9919+00	0.53950	
charge	-3.7035+01	-3.8886+01	-4.079 +01	-3.8417+01	-2.7723+01	-3.246 +01	-3.0077+01	-3.176 +01	-3.9466+01	-3.935 +01	0.10195	
discharge	6.1152+01	5.4741+01	4.6561+01	4.6657+01	6.1152+01	5.6533+01	4.6561+01	4.1807+01	5.0061+01	4.625 +01	0.00162	
$\bar{P}_B$ loss, watts	3.5878+02	3.5846+02	5.7691+02	5.774 +02	2.8768+02	2.8369+02	4.1341+02	4.1442+02	3.1519+02	2.8866+02	8.349 -01	
$\bar{I}_A$	4.2329+01	4.3859+01	4.4649+01	3.8141+01	4.241 +01	5.0006+01	4.4832+01	4.3964+01	3.9513+01	3.9446+01	8.2369-01	
drive probability	0.70495	0.07495	0.70090	0.70090	0.70495	0.70495	0.70090	0.70090	0.70259	0.70341	9.258 -01	
regen probability	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	8.8439-01	
charge probability	0.63519	0.58381	0.61718	0.55921	0.63519	0.63751	0.61718	0.56387	0.55190	0.57420	5.5402-01	
α set equal to one in drive	0.10584	0.10584	0.10177	0.10177	0.29484	0.29484	0.29882	0.29882	0.10271	0.10195	6.7609-01	
Remarks	0.00007	0.00007	0.00407	0.00407	0.00007	0.00007	0.00407	0.00407	0.00238	0.00162	1.1589+03	
											2.8907+02	

(← no regeneration →)

TABLE 5.4
PERFORMANCE OF FULL VOLTAGE SERIES SYSTEM
COMPONENTS ON LA-4 MISSION

TABLE 5.5
PERFORMANCE OF PARALLEL (EMT) S
COMPONENTS ON LA-4 MISSIO

Run	P	Q	S	T
Urban Engine Power, hp	15	13	15	13
Battery Resistance, $10^3\Omega$	86	86	172	86
Motor-Wheel Gear Ratio	1:1	1:1	1:1	variable
Planetary Gear Efficiency	90	90	90	90
Differential Gear Efficiency	97-94	97-94	97-94	97-94
$\bar{P}_R$, hp	6.9119+00	6.9119+00	6.8797+00	6.8721+00
in drive	2.2747+01	2.0063+01	2.2671+01	1.9986+01
in regen	-2.0446+00	-3.5357+00	-2.0446+00	-3.5357+00
$\bar{P}_{IC}$, hp	1.6217+01	1.4423+01	1.6212+01	1.442 +01
P_O, hp	7.5556+00	6.88 +00	7.549 +00	6.8753+00
in drive	7.9586+00	7.228 +00	7.9407+00	7.2187+00
in regen+	8.3436+00	7.9167+00	8.3436+00	7.9167+00
in regen-	6.1425+00	5.4345+00	6.1425+00	5.4345+00
$P_o n_{gM}^-$	6.0197+00	5.3258+00	6.0197+00	5.3258+00
$P_R n_{gI}^-$	-1.0894+01	-1.0894+01	-1.0894+01	1.0894+01
$\bar{P}_{Mo}$, hp	1.723 +01	1.7261+01	1.716 +01	1.7173+01
$\bar{P}_M$, hp	1.1384+01	1.1431+01	1.1361+01	1.1399+01
in drive	1.5586+01	1.3535+01	1.5524+01	1.3465+01
in regen	-9.0082+00	-9.7593+00	-9.0082+00	-9.7593+00
$\bar{P}_{Mi}$, hp	1.165 +01	1.1839+01	1.1624+01	1.1597+01
in drive	1.9171+01	1.6641+01	1.9105+01	1.5597+01
in regen	-7.3963+00	-8.0237+00	-7.3963+00	-8.4226+00
$\bar{T}_M$	5.5273+01	5.527 +01	5.5254+01	2.8047+01
$\bar{I}_M$	2.3501+02	2.347 +02	2.3493+02	1.4444+02
I_M	1.8401+02	1.8274+02	1.8394+02	1.1963+02
in drive	2.2738+02	2.0143+02	2.2723+02	1.2999+02
in regen	-1.5948+02	-1.679 +02	-1.5948+02	-1.1142+02
$\bar{I}_{PCUM}$	5.8983+01	6.01 +01	6.2048+01	5.6697+01
I_{PCUM}	3.7049+01	3.8284+01	3.8163+01	3.6824+01
in drive	6.9008+01	6.0495+01	7.2622+01	5.4594+01
in regen	-1.8972+01	-2.064 +01	-1.8688+01	-2.2721+01
$\bar{I}_B$	-4.4152+00	5.4935-01	-2.9197+00	-3.224 +00
charge	-3.8045+01	-3.6725+01	-3.7496+01	-3.8346+01
discharge	5.3322+01	5.0676+01	5.6492+01	4.6298+01
$\bar{P}_{PCUM}$	2.7952+00	3.3751+00	2.8126+00	2.4936+00
in drive	1.6006+01	1.4023+01	1.6143+01	1.27 +01
in regen	-4.677 +00	-5.0839+00	-4.7208+00	-5.6067+00
$\hat{P}_{Ai}$	6.3755+00	5.5255+00	6.3755+00	5.526 +00
$\bar{P}_{Ai}$	5.8536+00	5.0731+00	5.8536+00	5.0738+00
$\hat{P}_{Ao}$	5.3933+00	4.6227+00	5.3933+00	4.6231+00
$\bar{P}_{Ao}$	4.8754+00	4.162 +00	4.8754+00	4.1626+00
$\bar{I}_A$	4.0912+01	3.4698+01	4.0912+01	3.47 +01
$\bar{I}_{PCUA}$	1.921 +01	1.6425+01	1.9175+01	1.6401+01
$\bar{P}_{PCUA}$	4.628 +00	3.9496+00	4.628 +00	3.9502+00
$\bar{P}_B$	-1.3551+00	-1.6684-01	-1.3389+00	-1.0497+00
charge	-9.3176+00	-8.9915+00	-9.3572+00	-9.4023+00
discharge	1.2315+01	1.17 +01	1.2438+01	1.0727+01
drive probability	0.36119	0.44261	0.36089	0.44217
regen+ probability	0.63859	0.55717	0.63859	0.55717
regen- probability	0.29476	0.29476	0.29476	0.29476
charge probability	0.63179	0.57340	0.63179	0.58468
α set equal to one	0.32231	0.24089	0.32255	0.22554
in drive	0.00000	0.00000	0.00023	0.00044
in regen	0.32231	0.24089	0.32231	0.22510
Battery state change	charged	discharged	charged	charged

A

TABLE 5.5
PERFORMANCE OF PARALLEL (EMT) SYSTEM COMPONENTS ON LA-4 MISSION

	P	Q	S	T	U	V	W	Y
er, hp	15	13	15	13	15	13	13	13
ce, $10^3\Omega$	86	86	172	86	86	86	172	86
Ratio	1:1	1:1	1:1	variable	variable	variable	variable	variable
fficiency	90	90	90	90	80	80	80	90
r Efficiency	97-94	97-94	97-94	97-94	97-94	97-94	97-94	90-87
	6.9119+00	6.9119+00	6.8797+00	6.8721+00	6.8721+00	6.8721+00	6.6883+00	6.8675+00
	2.2747+01	2.0063+01	2.2671+01	1.9986+01	1.9986+01	1.9448+01	1.9121+01	1.9438+01
	-2.0446+00	-3.5357+00	-2.0446+00	-3.5357+00	-3.5357+00	-3.8028+00	-3.8028+00	-3.8028+00
	1.6217+01	1.4423+01	1.6212+01	1.442 +01	1.6559+01	1.4765+01	1.4747+01	1.4639+01
	7.5556+00	6.88 +00	7.549 +00	6.8753+00	6.988 +00	6.3874+00	6.3615+00	7.0715+00
	7.9586+00	7.228 +00	7.9407+00	7.2187+00	7.3618+00	6.5345+00	6.4788+00	7.2783+00
	8.3436+00	7.9167+00	8.3436+00	7.9167+00	7.9703+00	7.869 +00	7.869 +00	8.5697+00
	6.1425+00	5.4345+00	6.1425+00	5.4345+00	5.5525+00	4.9231+00	4.9231+00	5.5005+00
	6.0197+00	5.3258+00	6.0197+00	5.3258+00	5.4414+00	4.8247+00	4.8247+00	5.3905+00
	-1.0894+01	-1.0894+01	-1.0894+01	1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0101+01
	1.723 +01	1.7261+01	1.716 +01	1.7173+01	1.7165+01	1.722 +01	1.6931+01	1.771 +01
	1.1384+01	1.1431+01	1.1361+01	1.1399+01	1.1382+01	1.1482+01	1.1345+01	1.186 +01
	1.5586+01	1.3535+01	1.5524+01	1.3465+01	1.3318+01	1.36 +01	1.3314+01	1.4426+01
	-9.0082+00	-9.7593+00	-9.0082+00	-9.7593+00	-9.8453+00	-9.6844+00	-9.6844+00	-9.6829+00
	1.165 +01	1.1839+01	1.1624+01	1.1597+01	1.1561+01	1.1756+01	1.1604+01	1.2173+01
	1.9171+01	1.6641+01	1.9105+01	1.5597+01	1.5424+01	1.5758+01	1.5449+01	1.6671+01
	-7.3963+00	-8.0237+00	-7.3963+00	-8.4226+00	-8.4963+00	-8.3595+00	-8.3595+00	-8.3561+00
	5.5273+01	5.527 +01	5.5254+01	2.8047+01	2.8045+01	2.8073+01	2.7959+01	2.8694+01
	2.3501+02	2.347 +02	2.3493+02	1.4444+02	1.4445+02	1.4443+02	1.4398+02	1.4688+02
	1.8401+02	1.8274+02	1.8394+02	1.1963+02	1.1969+02	1.1941+02	1.1905+02	1.2167+02
	2.2738+02	2.0143+02	2.2723+02	1.2999+02	1.2919+02	1.3014+02	1.2939+02	1.3502+02
	-1.5948+02	-1.679 +02	-1.5948+02	-1.1142+02	-1.1216+02	-1.1031+02	-1.1031+02	-1.1033+02
	5.8983+01	6.01 +01	6.2048+01	5.6697+01	5.6546+01	5.7391+01	5.8065+01	6.0038+01
	3.7049+01	3.8284+01	3.8163+01	3.6824+01	3.6679+01	3.7516+01	3.7726+01	3.895 +01
	6.9008+01	6.0495+01	7.2622+01	5.4594+01	5.4022+01	5.5144+01	5.6254+01	5.8281+01
	-1.8972+01	-2.064 +01	-1.8688+01	-2.2721+01	-2.2916+01	-2.2552+01	-2.2092+01	-2.2542+01
	-4.4152+00	5.4935-01	-2.9197+00	-3.224 +00	-4.0053+00	2.2748-01	8.5209-01	-1.6418-01
	-3.8045+01	-3.6725+01	-3.7496+01	-3.8346+01	-3.6211+01	-3.5311+01	-3.4703+01	-3.751 +01
	5.3322+01	5.0676+01	5.6492+01	4.6298+01	5.1261+01	4.9464+01	5.0433+01	5.1581+01
	2.7952+00	3.3751+00	2.8126+00	2.4936+00	2.4083+00	2.8782+00	2.7531+00	3.2017+00
	1.6006+01	1.4023+01	1.6143+01	1.27 +01	1.2569+01	1.282 +01	1.2632+01	1.3518+01
	-4.677 +00	-5.0839+00	-4.7208+00	-5.6067+00	-5.6556+00	-5.5617+00	-5.5833+00	-5.5553+00
	6.3755+00	5.5255+00	6.3755+00	5.526 +00	5.6677+00	4.912 +00	4.9151+00	5.526 +00
	5.8536+00	5.0731+00	5.8536+00	5.0738+00	5.2039+00	4.51 +00	4.514 +00	5.0738+00
	5.3933+00	4.6227+00	5.3933+00	4.6231+00	4.7519+00	4.0651+00	4.0679+00	4.6231+00
	4.8754+00	4.162 +00	4.8754+00	4.1626+00	4.2817+00	3.6453+00	3.649 +00	4.1626+00
	4.0912+01	3.4698+01	4.0912+01	3.47 +01	3.5736+01	3.0189+01	3.0199+01	3.47 +01
	1.921 +01	1.6425+01	1.9175+01	1.6401+01	1.6868+01	1.4373+01	1.4375+01	1.6418+01
	4.628 +00	3.9496+00	4.628 +00	3.9502+00	4.0636+00	3.4574+00	3.461 +00	3.9502+00
	-1.3551+00	-1.6684-01	-1.3389+00	-1.0497+00	-1.2367+00	-2.2308-01	-3.5008-01	-3.4182-01
	-9.3176+00	-8.9915+00	-9.3572+00	-9.4023+00	-8.879 +00	-8.6558+00	-8.6742+00	-9.189 +00
	1.2315+01	1.17 +01	1.2438+01	1.0727+01	1.1877+01	1.146 +01	1.1243+01	1.1916+01
	0.36119	0.44261	0.36089	0.44217	0.44217	0.45882	0.45610	0.45878
	0.63859	0.55717	0.63859	0.55717	0.55717	0.54052	0.54052	0.54052
	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476
	0.63179	0.57340	0.63179	0.58468	0.63140	0.58041	0.58041	0.58041
	0.32231	0.24089	0.32255	0.22554	0.22554	0.20889	0.21155	0.20893
	0.00000	0.00000	0.00023	0.00044	0.00044	0.00044	0.00310	0.00048
	0.32231	0.24089	0.32231	0.22510	0.22510	0.20845	0.20845	0.20845
nge	charged	discharged	charged	charged	charged	discharged	discharged	charged

B

TABL
PERFORMANCE OF PA
COMPONENTS O

Run	T	TA	TAA	X	XA	EE	
Urban Engine Power, hp	13	11	11.75	15	13.6	15	
Battery Resistance, $10^3\Omega$	86	86	86	172	172	172	
Motor-Wheel Gear Ratio	variable	variable	variable	variable	variable	variable	va
Planetary Gear Efficiency	90	90	90	80	80	80	9
Differential Gear Efficiency	97-94	97-94	97-94	97-94	97-94	97-94	
$\bar{P}_R$, hp	6.8721+00	6.8721+00	6.8721+00	6.6883+00	6.6883+00	6.6883+00	6.
in drive	1.9986+01	1.928 +01	1.9448+01	1.9651+01	1.9121+01	1.9651+01	2.
in regen	-3.5357+00	-3.8712+00	-3.8028+00	-3.5357+00	-3.8028+00	-3.5357+00	-2.
$\bar{P}_{IC}$, hp	1.442 +01	1.2626+01	1.3299+01	1.6543+01	1.5286+01	1.6543+01	1.
$\bar{P}_O$, hp	6.8753+00	6.1997+00	6.4531+00	6.9621+00	6.5417+00	6.9621+00	8.
in drive	7.2178+00	6.2667+00	6.6184+00	7.3054+00	6.7094+00	7.3054+00	8.
in regen+	7.9167+00	7.8736+00	7.8968+00	7.9703+00	7.9452+00	7.9703+00	8.
in regen-	5.4345+00	4.7265+00	4.992 +00	5.5525+00	5.1119+00	5.5525+00	6.
$\bar{P}_o\eta_{gM}$(-)	5.3258+00	4.6319+00	4.8921+00	5.4414+00	5.0097+00	5.4414+00	6.
$\bar{P}_R\eta_{g1}$(-)	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.
$\hat{P}_{Mo}$, hp	1.7173+01	1.7244+01	1.7212+01	1.6882+01	1.6913+01	1.2013+01	1.
$\bar{P}_{Mo}$, hp	1.1399+01	1.1519+01	1.1469+01	1.1246+01	1.1311+01	5.7427+00	5.
in drive	1.3465+01	1.3699+01	1.3515+01	1.3023+01	1.3079+01	1.3023+01	1.
in regen	-9.7593+00	-9.6319+00	-9.7335+00	-9.8453+00	-9.8192+00	0. +00	0.
$\bar{P}_{Mi}$, hp	1.1597+01	1.1822+01	1.1733+01	1.141 +01	1.1541+01	6.6609+00	6.
in drive	1.5597+01	1.5873+01	1.5659+01	1.5106+01	1.5175+01	1.5106+01	1.
in regen	-8.4226+00	-8.3146+00	-8.4018+00	-8.4963+00	-8.4757+00	0. +00	0.
$\bar{\eta}_M$, drive	8.6334-01	8.6304-01	8.6308-01	8.6215-01	8.6186-01	8.6215-01	8.
$\bar{\eta}_M$, regen	8.6302-01	8.6323-01	8.6318-01	8.6298-01	8.6316-01	0. +00	0.
$\hat{I}_M$	2.8047+01	2.8089+01	2.8068+01	2.7933+01	2.7948+01	1.993 +01	1.
$\acute{I}_M$	1.4444+02	1.4446+02	1.4442+02	1.4402+02	1.4397+02	1.0156+02	9.
$\bar{I}_M$	1.1963+02	1.1936+02	1.1943+02	1.1933+02	1.191 +02	5.6628+01	5.
in drive	1.2999+02	1.3052+02	1.2967+02	1.2842+02	1.2811+02	1.2842+02	1.
in regen	-1.1142+02	-1.097 +02	-1.1075+02	-1.1216+02	-1.115 +02	0. +00	0.
I_M max	8.8842+02	8.8842+02	8.8842+02	8.8842+02	8.8842+02	8.8842+02	8.
$\hat{I}_{PCUM}$	5.6697+01	5.7675+01	5.7294+01	5.7029+01	5.7744+01	4.9459+01	4.
$\bar{I}_{PCUM}$	3.6824+01	3.7785+01	3.7427+01	3.6794+01	3.7454+01	2.4253+01	2.
in drive	5.4594+01	5.553 +01	5.4813+01	5.5004+01	5.5292+01	5.5004+01	6.
in regen	-2.2721+01	-2.2422+01	-2.2669+01	-2.2432+01	-2.2401+01	0. +00	0.
$\hat{I}_B$	-3.224 +00	1.5482+00	-2.2727-01	-3.4135+00	-4.0928-01	9.0248+00	2.
charge	-3.8346+01	-3.4038+01	-3.5745+01	-3.5561+01	-3.5871+01	-1.6836+01	-2.
discharge	4.6298+01	5.0851+01	4.8981+01	5.2164+01	4.9042+01	4.7715+01	4.
$\bar{P}_B$ loss, watts	2.7575+02	2.786 +02	2.7705+02	5.5086+02	5.5613+02	3.6256+02	3.
$\bar{P}_{PCUM}$	2.4936+00	3.0264+00	2.8276+00	2.283 +00	2.6141+00	5.4566+00	4.
in drive	1.27 +01	1.2907+01	1.2745+01	1.2375+01	1.2423+01	1.2375+01	1.
in regen	-5.6067+00	-5.5286+00	-5.5909+00	-5.6767+00	-5.6636+00	0. +00	0.
$\hat{\eta}_{PCUM}$, drive	9.1576-01	9.1706-01	9.162 -01	9.1027-01	9.1086-01	9.1027-01	9.
$\bar{\eta}_{PCUM}$, regen	8.9267-01	8.9167-01	8.9236-01	8.9599-01	8.9609-01	0. +00	0.
$\hat{P}_{Ai}$	5.526 +00	4.6758+00	4.9946+00	5.6713+00	5.142 +00	5.6713+00	7.
$\bar{P}_{Ai}$	5.0738+00	4.2932+00	4.5859+00	5.2085+00	4.7223+00	5.2085+00	6.
$\hat{P}_{Ao}$	4.6231+00	3.8516+00	4.1394+00	4.7551+00	4.2724+00	4.7551+00	5.
$\bar{P}_{Ao}$	4.1626+00	3.4495+00	3.7132+00	4.2859+00	3.8359+00	4.2859+00	5.
$\bar{\eta}_A$	8.2041-01	8.0349-01	8.0968-01	8.2287-01	8.1229-01	8.2287-01	8.
$\bar{I}_A$	3.47 +01	2.8528+01	3.0762+01	3.5745+01	3.1778+01	3.5745+01	4.
$\bar{I}_{PCUA}$	1.6401+01	1.3603+01	1.464 +01	1.6843+01	1.5103+01	1.6957+01	2.
P_{PCUA}	3.9502+00	3.2705+00	3.5222+00	4.0677+00	3.6395+00	4.0677+00	5.
$\bar{\eta}_{PCUA}$	9.4898-01	9.4808-01	9.4856-01	9.4909-01	9.4878-01	9.4909-01	9.
$\bar{P}_B$	-1.0497+00	9.2779-02	-3.3184-01	-1.37 +00	-6.5441-01	1.8035+00	3.
charge	-9.4023+00	-8.3432+00	-8.7625+00	-8.8928+00	-8.9656+00	-4.1048+00	-5.
discharge	1.0727+01	1.178 +01	1.1348+01	1.1635+01	1.0935+01	1.0643+01	1.
drive probability	.44217	.46373	.45882	0.43945	0.45610	0.43945	0.
regen+ probability	.55717	.53561	.54052	0.55717	0.54052	0.55717	0.
regen- probability	.29476	.29476	.29476	0.29476	0.29476	0.29476	0.
charge probability	.58468	.58041	.58041	0.63140	0.58041	0.59735	0.
α set equal to one	.22554	.20398	.20889	0.22820	0.21155	0.56027	0.
in drive	.00044	.00044	.00044	0.00310	0.00310	0.00310	0.
in regen	.22510	.20354	.20843	0.22510	0.20845	0.55717	0.

(P_M = 0 in

Remarks

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TABLE 5.6
RFORMANCE OF PARALLEL (EMT) SYSTEM
COMPONENTS ON LA-4 MISSION

EE	EEA	KK	KKA	LLA	R	RA	CC	CCA	JJ	JJA
15	18.6	15	17	17.25	15	14.9	15.0	19.7		17.8
172	172	172	172	172	86	86	86	86	86	86
variable	variable	variable	variable	variable	1:1	1:1	1:1	1:1	1:1	1:1
80	80	80	80	80	80	80	80	80		80
97-94	97-94	97-94	97-94	97-94	97-94	97-94	97-94	97-94	97-94	97-94
6.6883+00	6.7267+00	6.6883+00	6.6883+00	6.7267+00	6.9119+00	6.9119+00	6.9119+00	6.9119+00	6.9119+00	6.9119+00
1.9651+01	2.2346+01	1.9651+01	2.2264+01	2.2346+01	2.0063+01	2.0063+01	2.0063+01	2.363 +01	2.0063+01	2.2747+01
3.5357+00	-2.0446+00	-3.5357+00	-2.0446+00	-2.0446+00	-3.5357+00	-3.5357+00	-3.5357+00	-1.4939+00	-3.5357+00	-2.0446+00
1.6543+01	1.9775+01	1.6543+01	1.8339+01	1.8563+01	1.6562+01	1.6473+01	1.6562+01	2.0777+01	1.6562+01	1.9073+01
6.9621+00	8.0443+00	6.9621+00	7.5626+00	7.6387+00	6.9926+00	6.9626+00	6.9926+00	8.4038+00	6.9926+00	7.8333+00
7.3054+00	8.4922+00	7.3054+00	7.9215+00	8.0127+00	7.3719+00	7.3336+00	7.3719+00	8.6759+00	7.3719+00	8.2864+00
7.9703+00	8.7422+00	7.9703+00	8.3725+00	8.4303+00	7.9703+00	7.956 +00	7.9703+00	9.2499+00	7.9703+00	8.5573+00
5.5525+00	6.6854+00	5.5525+00	6.1819+00	6.2605+00	5.5525+00	5.521 +00	5.5525+00	7.0315+00	5.5525+00	6.4336+00
5.4414+00	6.5517+00	5.4414+00	6.0582+00	6.1353+00	5.4414+00	5.4106+00	5.4414+00	6.8909+00	5.4414+00	6.3049+00
1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01	-1.0894+01
1.2013+01	1.1516+01	1.287 +01	1.2678+01	1.2753+01	1.7253+01	1.7255+01	1.2548+01	1.1783+01	1.3368+01	1.3107+01
5.7427+00	5.2578+00	8.0247+00	8.002 +00	8.0456+00	1.1414+01	1.1418+01	5.9274+00	5.2771+00	8.2022+00	8.2082+00
1.3023+01	1.462 +01	1.3023+01	1.5117+01	1.5109+01	1.3389+01	1.3428+01	1.3389+01	1.5773+01	1.3389+01	1.5252+01
0. +00	0. +00	-4.0818+00	-4.0125+00	-4.0786+00	-9.8453+00	-9.8224+00	0. +00	0. +00	-4.0818+00	-4.2239+00
5.6609+00	6.0948+00	8.5449+00	8.4214+00	8.4563+00	1.1798+01	1.1809+01	7.2881+00	6.4981+00	9.1477+00	8.9812+00
1.5106+01	1.6948+01	1.5106+01	1.7526+01	1.7511+01	1.6462+01	1.651 +01	1.6462+01	1.9422+01	1.6462+01	1.8767+01
0. +00	0. +00	-3.3698+00	-3.3164+00	-3.371 +00	-8.093 +00	-8.0745+00	0. +00	0. +00	-3.3368+00	-3.446 +00
8.6215-01	8.6266-01	8.6215-01	8.6255-01	8.6284-01	8.133 -01	8.1331-01	8.133 -01	8.1209-01	8.133 -01	8.127 -01
0. +00	0. +00	8.2558-01	8.2651-01	8.265 -01	8.2202-01	8.2205-01	0. +00	0. +00	8.1748-01	8.1583-01
1.993 +01	1.9175+01	2.0657+01	2.0375+01	2.0394+01	5.5264+01	5.5265+01	3.963 +01	3.7502+01	4.078 +01	3.9995+01
1.0156+02	9.741 +01	1.1531+02	1.1503+02	1.1519+02	2.3471+02	2.3471+02	1.6719+02	1.5811+02	1.8242+02	1.8137+02
5.6628+01	5.055 +01	9.6014+01	9.686 +01	9.7127+01	1.8285+02	1.8282+02	8.8502+01	7.7344+01	1.4059+02	1.4332+02
1.2842+02	1.4056+02	1.2842+02	1.4363+02	1.4335+02	1.9991+02	2.0031+02	1.9991+02	2.3117+02	1.9991+02	2.239 +02
0. +00	0. +00	-7.0451+01	-7.0637+01	-7.1164+01	-1.693 +02	-1.6892+02	0. +00	0. +00	-9.3482+01	-9.7752+01
8.8842+02	8.8842+02	8.8842+02	8.8842+02	8.8842+02	8.9158+02	8.9187+02	8.9158+02	8.8842+02	8.9158+02	8.8842+02
.9459+01	4.7305+01	5.0511+01	4.9205+01	4.9531+01	5.9906+01	5.9958+01	5.3548+01	5.0222+01	5.4446+01	5.2653+01
.4253+01	2.2005+01	2.8761+01	2.7789+01	2.788 +01	3.8117+01	3.8162+01	2.6512+01	2.3345+01	3.0621+01	2.931 +01
.5004+01	6.1191+01	5.5004+01	6.3207+01	6.3202+01	5.9886+01	6.0049+01	5.9886+01	6.9777+01	5.9886+01	6.7618+01
. +00	0. +00	-8.0627+00	-7.9325+00	-8.0452+00	-2.0824+01	-2.0775+01	0. +00	0. +00	-7.3735+00	-7.644 +00
.0248+00	2.8011+00	4.5423+00	2.224 -01	-9.6744-02	-2.4234-01	-3.0666-02	1.1315+01	2.8869+00	7.2173+00	1.2483+00
.6836+01	-2.1209+01	-2.3003+01	-2.7035+01	-2.7168+01	-3.7002+01	-3.7258+01	-1.8158+01	-2.2686+01	-2.4152+01	-2.7866+01
.7715+01	4.5724+01	5.2164+01	4.8307+01	4.9085+01	5.0633+01	5.0033+01	4.6831+01	4.8365+01	5.0633+01	5.1234+01
.6256+02	3.3993+02	3.9255+02	3.8144+02	3.8789+02	2.9758+02	2.978 +02	2.1269+02	1.9193+02	2.2611+02	2.1681+02
.4566+00	4.9622+00	4.3507+00	3.8666+00	3.8502+00	3.2878+00	3.3112+00	6.1467+00	5.423 +00	5.1496+00	4.4832+00
.2375+01	1.3798+01	1.2375+01	1.424 +01	1.4227+01	1.3884+01	1.3921+01	1.3884+01	1.6209+01	1.3884+01	1.5692+01
. +00	0. +00	-1.9782+00	-1.9493+00	-1.9774+00	-5.13 +00	-5.1177+00	0. +00	0. +00	-1.7893+00	-1.8569+00
.1027-01	9.159 -01	9.1027-01	9.178 -01	9.1781-01	8.8415-01	8.8435-01	8.8415-01	8.9353-01	8.8415-01	8.918 -01
. +00	0. +00	7.8723-01	7.8823-01	7.8665-01	8.5004-01	8.4995-01	0. +00	0. +00	7.1912-01	7.2261-01
.6713+00	7.0307+00	5.6713+00	6.4275+00	6.5204+00	5.6671+00	5.6294+00	5.6671+00	7.4429+00	5.6671+00	6.725 +00
.2085+00	6.4565+00	5.2085+00	5.9029+00	5.9879+00	5.2032+00	5.1685+00	5.2032+00	6.8336+00	5.2032+00	6.1745+00
.7551+00	5.9939+00	4.7551+00	5.4403+00	5.5251+00	4.7514+00	4.717 +00	4.7514+00	6.3804+00	4.7514+00	5.712 +00
.2859+00	5.4305+00	4.2859+00	4.9204+00	4.9983+00	4.281 +00	4.2492+00	4.281 +00	5.7824+00	4.281 +00	5.1694+00
.2287-01	8.4108-01	8.2287-01	8.3354-01	8.3473-01	8.2276-01	8.2213-01	8.2276-01	8.4617-01	8.2276-01	8.3721-01
.5745+01	4.5698+01	3.5745+01	4.1264+01	4.1952+01	3.5734+01	3.5457+01	3.5734+01	4.8747+01	3.5734+01	4.3461+01
.6957+01	2.1383+01	1.6929+01	1.9376+01	1.9678+01	1.6892+01	1.6767+01	1.6945+01	2.2812+01	1.6933+01	2.0403+01
.0677+00	5.155 +00	4.0677+00	4.6709+00	4.7449+00	4.0629+00	4.0327+00	4.0629+00	5.4886+00	4.0629+00	4.9072+00
.4909-01	9.4928-01	9.4909-01	9.493 -01	9.493 -01	9.4905-01	9.4903-01	9.4905-01	9.4919-01	9.4905-01	9.4927-01
.8035+00	3.3232-01	6.9759-01	-3.2822-01	-4.1128-01	-3.5574-01	-3.0526-01	2.5031+00	5.0086-01	1.5059+00	8.2516-02
.1048+00	-5.1888+00	-5.6291+00	-6.6282+00	-6.6627+00	-9.0597+00	-9.1223+00	-4.3928+00	-5.501 +00	-5.8528+00	-6.7625+00
.0643+01	1.0202+01	1.1635+01	1.0785+01	1.0946+01	1.169 +01	1.1552+01	1.0812+01	1.1174+01	1.169 +01	1.1834+01
.43945	0.35862	0.43945	0.35803	0.35862	0.44261	0.44261	0.44261	0.33449	0.44261	0.36119
.55717	0.63859	0.55717	0.63859	0.63859	0.55717	0.55717	0.55717	0.66529	0.55717	0.63859
.29476	0.29476	0.29476	0.29476	0.294.5	0.29476	0.29476	0.29476	0.29476	0.29476	0.29476
.59735	0.63948	0.63140	0.63606	0.64318	0.58041	0.57340	0.54636	0.63994	0.58041	0.63179
.56027	0.64111	0.23810	0.31952	0.31894	0.24089	0.24089	0.55717	0.66529	0.26506	0.34648
.00310	0.00252	0.00310	0.00310	0.00252	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
.55717	0.63859	0.23500	0.31641	0.31641	0.24089	0.24089	0.55717	0.66529	.26506	0.34648

P_M = 0 in regen)

($P_M = -P_o \eta_{gM}$ for $P_R < 0$)

(P_M = 0 in regen)

B

5.3.2 Effect of System Parameters on Parallel (EMT) System Performance

The planetary gear efficiency, η_{go}, is extremely important as it affects overall parallel system efficiency. Comparison of runs RA, Q, TAA and V shows the effect is almost proportional, i.e., by raising η_{go} from 80% to 90%, the system efficiency increases by 11%.

The differential gear efficiency has an effect similar to that of the series system. For example, raising η_{g1} from 90%-87% to 97%-94% rasis the overall efficiency from 70% to 77%.

Comparing runs RA and V, it can be seen that providing a variable gear ratio between the motor and propeller shaft is an effective means of raising system efficiency. In these cases, the efficiency increased by approximately 13%.

The effect of doubling battery impedance in a variable gear ratio parallel system is slight. In runs V and W the system efficiency changed by only 1.5%. Other run comparisons such as TAA vs. W, etc. indicate even a lesser change of 0.7%. This is distinctly less than the impact on the series system and is probably due to the higher drive line efficiency of the parallel system, which allows a larger component of engine power to flow directly to the wheels, thus diminishing the interchange of power with the battery.

The effect of not implementing regeneration in the parallel system is a reduction of overall efficiency by 13.5%-18% as seen in runs JAA, RA, LLA and XA.

Table 5.7 summarizes the effect of various parameter changes on the series and parallel systems.

TABLE 5.7

SUMMARY OF THE EFFECT OF PARAMETRIC CHANGES ON SERIES AND PARALLEL HYBRID SYSTEMS EFFICIENCY*

System	Incorporation of Variable Gear Ratio	Battery Impedance Inc. from 86 to 172	Gear 2 Eff. Degradation from 98-94 to 90-87	Gear 1 Eff. Degradation from 97-94 to 90-87	Planetary Gear g_0 Eff. Degradation from 90-80%	Absence of Regeneration
Series	↑ +15%	↓ -7%	↓ -8%	↓ -7%	not applicable	↓ -10%
Parallel	↑ +13%	↓ -1.5%	not applicable	↓ -9%	↓ -11%	↓ -13.5%

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*The increase or decrease in the efficiency is defined here as the quotient of the change in efficiency divided by level of efficiency prior to the particular parameter change. For example, run CA shows an efficiency level of 47.9% obtained with regeneration. Run AAA shows an efficiency level of 42.9% obtained when regeneration was not implemented. The change in efficiency is 5.0%; however, the decrease in system efficiency is

$$\frac{5.0}{47.9} \cong 10\%$$

A decrease in efficiency means that the prime mover will have to expend more energy, require more fuel to drive the car over the same route, and with all engine operating conditions the same will produce more emissions.

5.4 Ratings of the Electrical Portions of the Hybrid Power Trains

The computer simulation results are useful in evaluating the appropriateness of the ratings and specifications initially assumed in the component models. In all cases the original specifications of the motors, PCUs and alternators were validated.

Motor Ratings

The values of critical design parameters for the DC series traction motor generated on simulated runs of LA-4 operation are shown in Tables 5.8 and 5.9. In the case of the full voltage series hybrid, some of the design specifications are exceeded slightly when a single gear ratio is used between the motor and wheels. When a multi-step variable gear ratio is inserted none of the design ratings are exceeded.

While the ratings of the series system were based on high speed cruise demands, the motor of the parallel system is unloaded during high speed cruise. Rather it was rated on estimates of the effective duty cycle the motor would experience in stop-and-go urban traffic like LA-4. The simulation results show that with variable gearing the initial specifications can be met with a machine rated at 30 hp.

Motor PCU Ratings

The chopper PCU must be rated for a commutation current equal to the peak expected current at the lowest battery voltage. In addition, the PCU must be able to operate efficiently at the highest anticipated battery voltages.

The series system motor PCU was designed for 300% motor torque with a variable gear ratio. The chopper was rated at 144 KVA and was designed to put out 54 kw continuously. Table 5.10 summarizes the average power, and peak and average currents obtained from the simulations contrasted to the design ratings. Operation of the series system without variable gear ratio penalizes the PCU by increasing the rating requirement.

The peak motor PCU rating of the parallel system is equal to that of the full voltage series system; however, the continuous rating need only be equal to the effective duty cycle rating of normal operation. For the LA-4 cycle, the initial estimate of 22.5 kw was too high. Table 5.11 shows that the design current ratings are exceeded if a single gear ratio is used; if a variable gear ratio is used, the design ratings are never exceeded. In both the series and parallel systems, the RMS input current to the PCUs does not exceed 50% of the power SCR ratings.

Alternator-Rectifier

The continuous power rating of the series system alternator-rectifier is 58 kw--this rating is never approaches for LA-4 service as shown in Table 5.12.

Tables 5.13 and 5.14 show that the ratings of the parallel system alternator-rectifier and alternator PCU are conservative. The alternator and PCU both have more than a 50% power rating margin. The peak current rating of the PCU is met without gear shifting and is too conservative for the variable ratio case.

TABLE 5.8
Comparison of Design Ratings and LA-4 Simulation
Results for Series System Traction Motors

Parameter	Rating	Simulation Results Without Variable Gears (run CA)	With Variable Gears (run IA)
RMS power (hp)	65	20	19.9
RMS torque (ft-lbs)	74	89	46.6
RMS current (amps)	235	255	157

TABLE 5.9
Comparison of Design Ratings and LA-4 Simulation
Results for Parallel System Traction Motors

Parameter	Rating	Simulation Results Without Variable Gears (run O)	With Variable Gears (run TAA)
RMS power (hp)	30	17.2	17.2
RMS torque (ft-lbs)	22.5	55.3	27
RMS current (amps)	145	235	144
Peak Current (% rated)	300	---	300

TABLE 5.10
Comparison of Design Ratings and LA-4 Simulation Results for Series System Motor PCU

Parameter	Rating	Simulation Results: Without Variable Gearing	Simulation Results: With Variable Gearing
PCU power	54 kw 144 KVA	12.3 kw	11.4 kw
Average PCU Current (amps)	235	207	137
Peak PCU Current (amps)	600	770	450

TABLE 5.11
Comparison of Design Ratings and LA-4 Simulation Results for Parallel System Motor PCU

Parameter	Rating	Simulation Results: Without Variable Gearing	Simulation Results: With Variable Gearing
PCU power	22.5 kw 144 KVA	8.9 kw	8.9 kw
Average PCU Current (amps)	145	182	119
Peak PCU Current (amps)	600	800	450

TABLE 5.12
Comparison of Design Ratings and LA-4 Simulation Results for Series System Alternator

Parameter	Rating	Simulation Results Without Variable Gearing	 With Variable Gearing
Average Power (kw)	58	10.9	9
Average Current (amps)	235	44	36

TABLE 5.13
Comparison of Design Ratings and LA-4 Simulation Results for Parallel System Alternator

Parameter	Rating	Simulation Results Without Variable Gearing	 With Variable Gearing
RMS Power (kw)	10	4.6	4.1
Average Current (amps)	50	34.7	31
Peak Current (amps)	100	100	78

TABLE 5.14
Comparison of Design Ratings and LA-4 Simulation Results for Parallel System Alternator PCU

Parameter	Rating	Simulation Results Without Variable Gearing	 With Variable Gearing
RMS Power	10 kw 24 KVA	3.95	3.7
Average Current (amps)	50	35	31
Peak Current (amps)	100	100	75

6.0 ESTIMATES OF THE COST AND WEIGHT OF HYBRID FAMILY VEHICLES

6.1 Comparison of Series and Parallel Hybrid Systems

The first cost of a hybrid vehicle would be the summation of the various component costs at the original equipment manufacturer (OEM) level plus the costs of overhead, direct labor and profit added at the OEM level. To these costs must be added the mark-ups of the wholesaler and retailer. The vehicle price level is also affected by such things as the mix of available options, warranty costs and after-market sales.

A comparison of the relative costs of series and parallel systems at the OEM level can be easily made; those items of major difference between the two systems only need be compared to judge the relative costs of the two systems. Appendix H presents an extensive listing of the specification and estimated OEM price of various electrical and electronic components for the full voltage series and the parallel (EMT) power trains. Table 6.1 summarizes those costs along with the specific mechanical component costs which might differ between the two systems. It is assumed that in both systems, the engine, batteries, cooling systems and other power train components are similar. The differential gearing and a portion of the gearing which couples to the engine in both systems will be similar. The planetary gearing is treated as a cost increment for the parallel system.

The weight of both hybrid power train systems include the weights of the batteries, engine, auxiliaries and mechanical elements. The battery weight can be estimated from the results of TRW's work on lead-acid battery development. Power densities of 170 watts/pound have been achieved repeatedly. This power level is capable of providing adequate vehicle acceleration within a package weighing approximately 500 pounds.

The engine weight of the engine depends on the particular design which is ultimately adopted. The starter motor and alternator normally supplied on the engine can be eliminated; however, engine cooling systems, carburetion and induction systems will be similar to conventional automobiles. There probably will be additional weight penalties for catalytic control devices in addition to the muffler and exhaust pipes. The

TABLE 6.1

SUMMARY OF OEM COSTS AND WEIGHT COMPARISON
OF PARALLEL AND SERIES POWER TRAINS

Component	Parallel Hybrid			Series Hybrid		
	Rating	Cost ($)	Weight (pounds)	Rating	Cost ($)	Weight (pounds)
Series Motor	30 hp @ 7200 rpm, 240 VDC	200	160	65 hp @ 4650 rpm, 240 VDC	406	325
Motor PCU	144 KVA, 240 VDC (190 parts)	140	70	144 KVA, 240 VDC (190 parts)	150	88
Alternator and Rectifier	10 kw @ 12,000 rpm, 240 VDC	90	40	56 kw @ 12,000 rpm, 240 VDC	180	160
Alternator PCU	24 KVA, 240 VDC (177 parts)	113	50	--	--	--
Electronic Controls and Sensors	2.8 kw at 24 and 240 VDC	32	16	2.0 kw at 24 and 240 VDC	32	16
Planetary Gear	--	25	40	--	--	--
Totals		600	386		768	589

Chevrolet Vega engine which was used in the experimental portion of this study weighs approximately 350 pounds with coolant, lubricant, radiator, alternator and starter motor. Even ignoring these last two items, an engine weight of 350 pounds appears reasonable.

The other major power train elements of the hybrid vehicle will be:

Coupling gears between engine and power train--In the series system a simple 3:1 gear train could be used having only two elements. The planetary gearing of the parallel system would be more complex and heavier; however, it would not be vastly different from the planetary sets of conventional automatic transmissions.

Differential--Power would be supplied to the rear driving wheels through a conventional automotive type differential. In the series system, the motor would replace the propeller shaft of conventional arrangements. The parallel system would probably combine the traction motor mounting and connection with the differential case.

Variable gear ratio coupling--A manual or preferably automatic variable gear ratio could be built into the differential housing. An automatic system could use a single stage planetary arrangement with electrically actuated operation of the planet clutches for gear shifting. The ability to uncouple the engine from the driving wheels at idle would eliminate one need for a fluid coupling; however, smoothness of shifting might require at least a "soft" coupling between the motor shaft and differential.

A traction motor fan and a battery compartment fan would be needed, the former for cooling the motor, the latter to provide positive ventilation. Battery cooling does not appear to present a major problem--ram air cooling may provide satisfactory cooling flow for normal operation.

Power cables--Power cables will have to be provided between major electrical components. In view of the high current levels, heavy gage copper cable will be needed. Ease of installation suggests flexible, stranded cable be used throughout.

Fuel tank and gasoline--The fuel tank of the hybrid will be of about the size of present-day compact/sub-compact vehicles due to the high anticipated fuel economy of the hybrid.

Miscellaneous items--A variety of mounting brackets, connectors and actuators will be needed in the power train. Their detailed definition cannot be made without a near-complete blueprint of the vehicle.

Table 6.2 outlines the power train weights for the series and parallel systems, with and without variable gearing. Of the weight contributors, only major weight reductions could be made in the battery package. However, sizable reductions in battery weight presume a major battery technology advance. In view of the uncertainty involved of projecting say a 20-25% increase in battery power density without sacrificing life, a conservative estimate of a 500 pound battery package must be made.

6.2 Costs of Hybrid Vehicle Ownership

Lack of information related to the price mark-up from the OEM to the customer makes it difficult to estimate user costs including depreciation of all major power train components. It is clear from the OEM price of the electrical components of Table 6.1, that depreciation costs based on those numbers would involve at least $100/year.

It is possible however, to estimate the direct operating cost of hybrids associated with battery replacement and fuel usage. It is reasonable to assume a battery lifetime of three years and with advanced technology, five year replacement periods may be possible. Furthermore, since an internal combustion engine in the hybrid can be set to operate around peak economy by use of three-component catalytic control technique similar to the one described later in this report, the specific fuel consumption of the smaller displacement engine can be reasonably low. Data from the Vega suggests about 0.55 pounds of fuel/horsepower-hour at part throttle is possible.

Table 6.3 summarizes the direct operating costs of hybrid systems. Battery replacement costs to the consumer are taken at $1/pound.

Various emission control systems and devices are postulated for the 1975-76 automobiles. To comply with NO_x standards, manufacturers are planning on using rich air-fuel ratios, retarded spark timing, exhaust gas recirculation and lower compression ratios. Each of these approaches

TABLE 6.2

HYBRID VEHICLE POWER TRAIN WEIGHT

Power Train Component	Weight	
Engine (∿150 CID)	350	
Battery	500	
Engine gear coupling (g_2)	10*	40**
Differential (g_1)	50	
Variable gear ratio coupling	50***	
Traction motor fan	10	
Battery compartment ventilation fan	5	
Major power cables between alternator, batteries and motor (50 feet, #0 AWG stranded wire)	15	
Fuel tank and gasoline	80	
Miscellaneous electrical and mechanical elements such as mounting brackets, electrical interconnects, cable connectors	40	
Electronic and electrical equipment (see Table)	589*	361**

Totals	Parallel	Series
with variable gearing	1501	1699
without variable gearing	1451	1649

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*series only
**parallel only
***variable gearing optional

TABLE 6.3

HYBRID VEHICLE FUEL AND BATTERY COSTS

Fuel----------------------$0.0175/mile*

Battery Replacement-------$0.0075/mile (five-year battery)**
$0.0125/mile (three-year ")**

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*Fuel at 7.15 pounds/gal. costing $0.33/gal. Car travels at 22 mph on the average.

**Battery failure assumed related to cycle life under load; hence 50,000 mile/five-year battery is assumed to be 50% toward replacement after 25,000 miles, independent of time period to accumulate 25,000 miles. Three-year battery assumes 30,000 miles service.

tends to reduce fuel economy in conventional cars; some estimates run as high as 33% increased fuel consumption. Assuming this level of increase, then while the hybrid will get about 19 mpg, the conventional car will consume about 12.7 mph or will cost about $87 more in fuel than the hybrid for 10,000 miles of service.* If the five-year battery is assumed, the battery replacement costs are absorbed by fuel savings.

Other operating and maintenance procedures and costs required of the hybrids should be minimal. With proper electronic design, the PCUs and rotating machinery should be maintenance free. The PCUs would most likely be modularized. In the event of failure, diagnostic equipment at the service garage would identify the failed module which would be replaced by a simple plug-in arrangement. It is probable that rather than scrapping the module, defective parts would be recycled through a repair yard where they would be fixed and sold as a rebuilt unit (much the same that automotive parts such as alternators carburetors, etc. are handled today). It is even possible that rebuilt parts could be reassembled within new vehicles.

Brush life of the alternators should be extremely high--similar to that of present automotive alternators. DC motor brush life can be controlled by proper choice of brush material, contact pressure and

*Fuel cost changes due to using accessories such as air conditioning, power steering, etc. will be the same in hybrid and conventional cars.

conservative design of the machine's commutation. Brush lives of 50,000 seem possible. Occasional inspection of the brushes and commutator will be necessary to detect incipient problems and to blow out accumulated brush material dust.

There are several areas of reduced vehicle operating costs associated with the hybrids. Quasi-constant engine operation and the elimination of acceleration mixture enrichment and deceleration blow-by may reduce lubricating oil wear and extend the period between oil and oil filter changes. Spark plug failure due to deposit build-up may be reduced. There is no doubt that regenerative braking will increase brake life as well as providing a redundant braking means.

7.0 HYDROCARBON ACCUMULATOR MATERIALS SCREENING

A hydrocarbon accumulator is a device which is used to control the cold start hydrocarbon emissions from an engine. It operates on an adsorption-desorption cycle. The accumulator adsorbs exhaust hydrocarbons from the hydrocarbon-rich but relatively cool exhaust stream during start-up and retains them for a sufficient period during which the engine air-fuel ratio is leaned toward stoichiometry and the catalytic converter is heated to a point where effective hydrocarbon oxidation is possible. The bed is desorbed by one of several means and the trapped hydrocarbons are returned to the engine or catalyst for oxidation.

While the principle of hydrocarbon accumulator operation is simple, the selection of bed materials must be based on an assessment of adsorption-desorption properties, physical stability and cost. A screening of candidate materials was performed using the cold start hydrocarbons from a single cylinder of a four cylinder internal combustion engine.

7.1 Test Equipment and Procedures

A test canister was constructed to serve as a container for hydrocarbon accumulator material screening. A diagram of the canister is shown in Figure 7.1. The canister was constructed of stainless steel in a double-walled configuration. The material undergoing test was held between retainer screens set 1 1/2 inches (25 cubic inches) apart for the screening tests. Later the full six inches of bed were filled with selected adsorbent and used to control the cold start hydrocarbons during full scale emission tests of the hybrid system.

The outer jacket was constructed so that the engine exhaust could be circulated around the inner compartment to heat the accumulator material for desorption. The canister was positioned about six feet from the exhaust port of the #4 cylinder of a VW 1600 engine* and was connected so that the cylinder's exhaust could flow through the bed or jacket. A small line led from the outlet of the bed to the intake manifold of the engine. During the later full-scale emission tests a small bleed flow of exhaust was allowed to pass through the bed to the intake manifold while the major portion of the flow went through the jacket so that the bed could be desorbed during cold start testing. Thermocouples were

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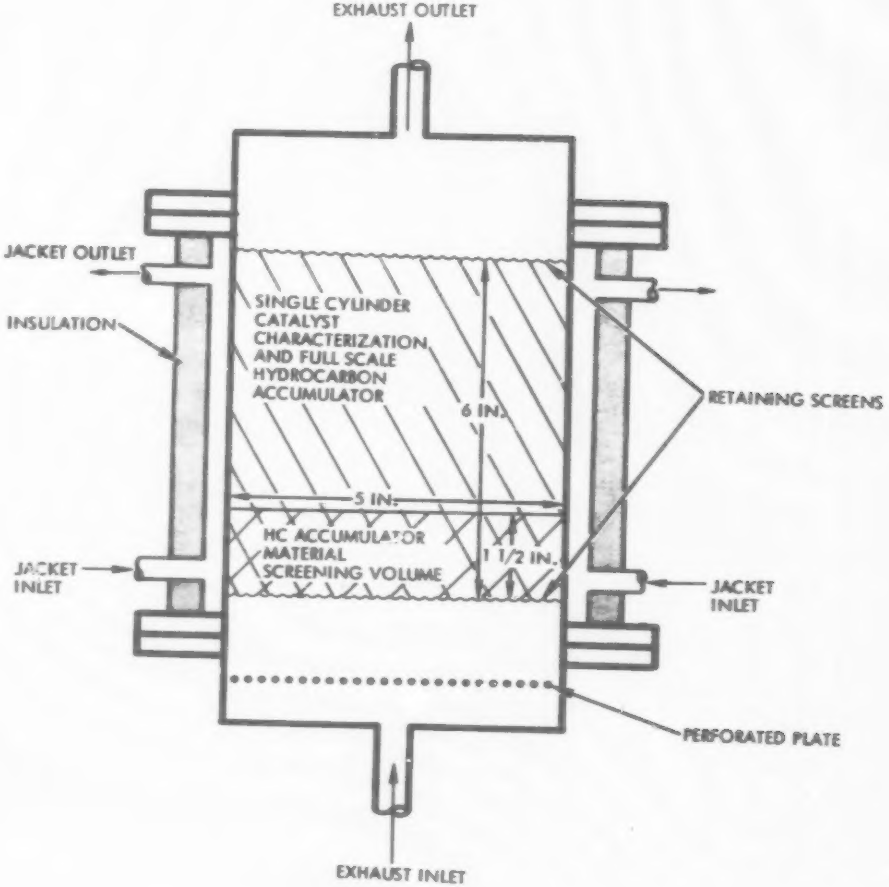
*A description of the engine and carburetion modifications can be found in Reference 1.

FIGURE 7.1

TEST CANISTER USED IN HYDROCARBON ACCUMULATOR SCREENING, SINGLE CYLINDER CHARACTERIZATION OF TRW-HARSHAW CATALYST AND FULL SCALE HYDROCARBON ACCUMULATOR


EXHAUST OUTLET
JACKET OUTLET
INSULATION
SINGLE CYLINDER CATALYST CHARACTERIZATION AND FULL SCALE HYDROCARBON ACCUMULATOR
6 IN.
RETAINING SCREENS
5 IN.
HC ACCUMULATOR MATERIAL SCREENING VOLUME
1 1/2 IN.
JACKET INLET
JACKET INLET
PERFORATED PLATE
EXHAUST INLET

placed within the bed to monitor its temperature. Exhaust sample taps and pressure taps were located upstream and downstream of the canister. The photograph of Figure 7.2 shows the general arrangement of the test canister on the EMT dynamometer stand.

The flow through the bed was vertically upward. Initial experiments showed that if the bed was not tightly packed, the bed would tend to lift and float and the resulting movement would cause the adsorbents to fracture. After several trial and error attempts a fill procedure was adopted in which the bed was packed by running a small air hammer against the canister allowing the bed to subside and pack itself into a minimum volume. A layer of fiber glass cloth was laid on top of the bed (outlet side) and a stainless steel retainer screen was drawn down by screws compressing the bed.

A fixed test procedure was adopted in an attempt to produce a reproducible set of cold start hydrocarbons-exhaust flow rates-gas stream temperature conditions. With the engine and accumulator bed initially at room temperature the engine was started. The electronic choke on the VW fuel injection system was turned on fully for ten seconds. During that period the engine would come up to 1800 rpm and the flow through the canister would come up to approximately 8 scfm (1/4 of the engine air flow). At the end of ten seconds, the choke was reduced to half the starting value where it remained for the next 50 seconds. After one minute the choke was completely removed leaving the engine operating essentially at stoichiometry. For the remainder of 20 minutes the exhaust was allowed to flow through the bed at constant engine rpm and manifold pressure. The nominal standard space velocity through the bed was 33,000 V/V/Hr. Actual space velocities ranged from 36,000 to 80,000 V/V/Hr. depending on the temperature of the exhaust.

During the test, the inlet and outlet CO, NO, HC and O_2 levels were continuously recorded along with the bed pressure drop and temperatures. Mass measurement of the accumulator hydrocarbon output was made during adsorption and desorption phases of the test cycle for many of the runs using a Beckman Constant Volume Sampling System (bag technique). In addition the inlet and outlet HC concentrations were integrated and averaged for the adsorption and desorption leg of each cycle. The

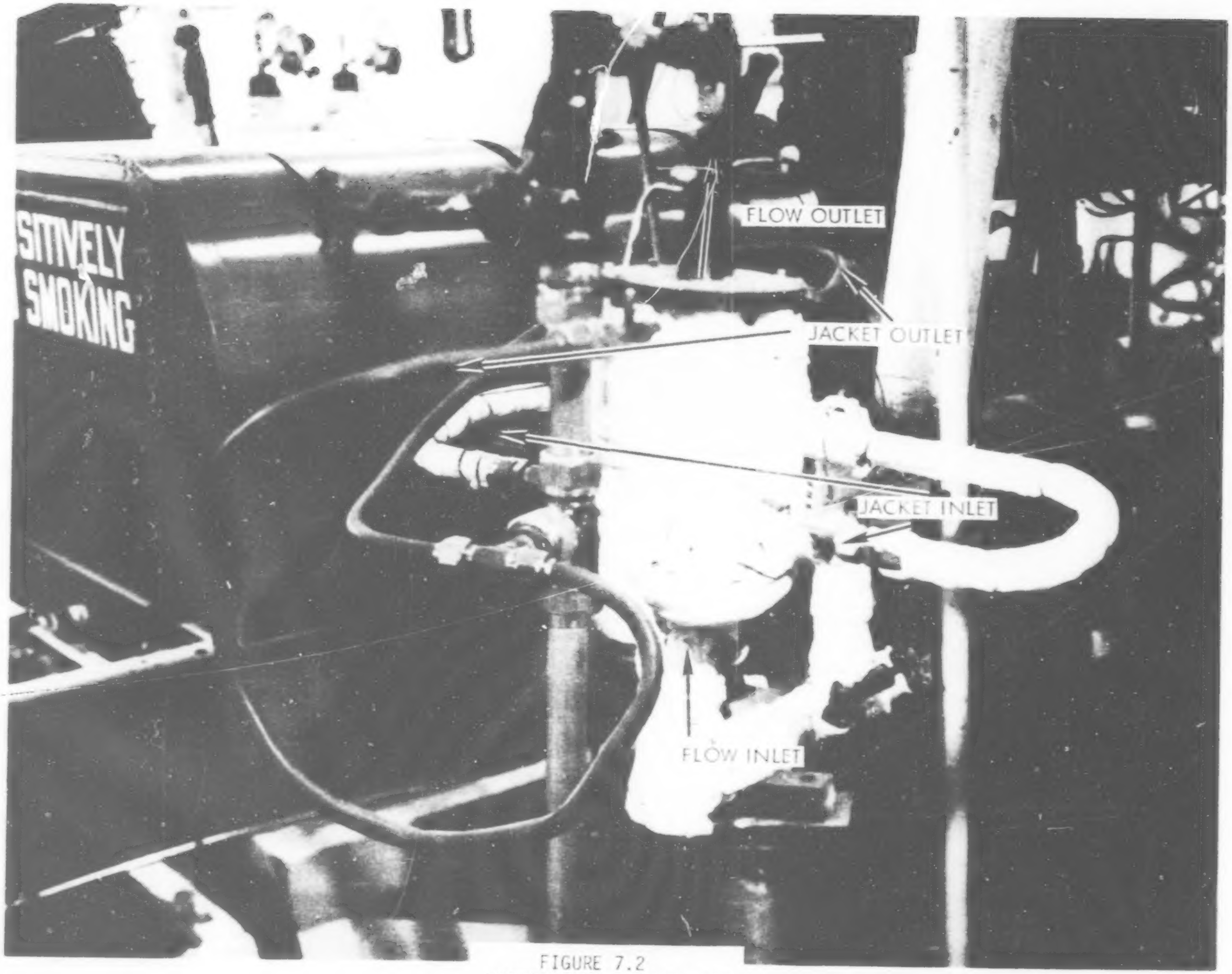

FLOW OUTLET
JACKET OUTLET
JACKET INLET
FLOW INLET
SITIVELY
SMOKING

FIGURE 7.2
HYDROCARBON ACCUMULATOR

product of the average concentrations, flow rate and hydrocarbon density were used to estimate the mass flow of HC into and out of the accumulator. The difference between these two quantities represents the mass of HC retained during adsorption and desorption. Comparison of the computed mass rates with those measured using the constant volume sampler showed reasonable agreement, generally within ±5% and supported the use of the integrated values as a means of estimating the adsorbed hydrocarbons.

7.2 Selection of Candidate Materials

Ten different types of adsorbents were originally selected as potential hydrocarbon accumulator materials. One of these, Porasieve, was eliminated for cost reasons. Its present price is approximately \$50/gram and even in large production quantities its price would drop only to \$50/pound. A second class of adsorbents composed of supported chromatographic materials such as sebacates, silicones, apiezones and tars were rejected because of stability problems above 250°F and their high cost.

The materials finally selected for screening were:

Barnaby-Chaney Nut Shell Activated Charcoal KE 9448
Barnaby-Chaney Activated Charcoal MI 8588
Nuchar Activated Carbon WVH 6x16 mesh
Davidson Molecular Sieve 10A - 13X mesh
Davidson Silica Gel 6x12 mesh
Linde Molecular Sieve 13X mesh
Pittsburgh Activated Charcoal BPL 4x6 mesh
Harshaw Activated Alumina 1/8" diameter pellets

The first material Barnaby-Chaney KE9448 was rejected after experiments. The material contained an excessive amount of fines some of which could not be removed by sieving. During the first test run over 50% of the bed was lost; during the second run the accumulator screen filters plugged causing excessive back pressure and engine misfire. Each of the remaining seven materials was tested at least twice using the cold start procedure previously outlined. Alumina was tested only once as it quickly lost its adsorption ability at temperatures just above ambient.

A graphical representation of typical data from one of the screening tests can be found in Figure 7.3. The inlet HC concentrations are those coming from the engine exhaust; the initially high values are a result of heavily choked-cold engine operation. The bed temperature rises in time as the exhaust gas sensible heat increases and the bed warms-up.

Two other quantities are shown in the figure. The first, termed holdup is defined as the ratio of bed outlet hydrocarbon concentrations minus the inlet concentrations divided by the inlet concentrations. Holdup is a measure of the instantaneous adsorption capability of the material. When holdup is positive the bed is adsorbing; when it is negative the bed is desorbing. The temperature or time at which holdup falls from a positive value to zero is referred to as the crossover temperature or crossover time.

Retention is defined as the mass of hydrocarbons residing in the bed at some time divided by the total mass of hydrocarbons which entered the bed up to that particular time. Retention is computed by subtracting the total outlet HC mass flow from inlet mass flow & dividing by inlet flow.

The data from the screening of the remaining seven materials is presented in the table of Appendix I. The data lists a short description of each material, its weight for an initial fill volume of approximately 25 cubic inches and temperature at various times after cold start. Holdup, crossover temperature and time are shown. In addition the average inlet and outlet hydrocarbon concentrations during adsorption and desorption phases are indicated. These latter data are useful in computing the retention at various times within the test cycle.

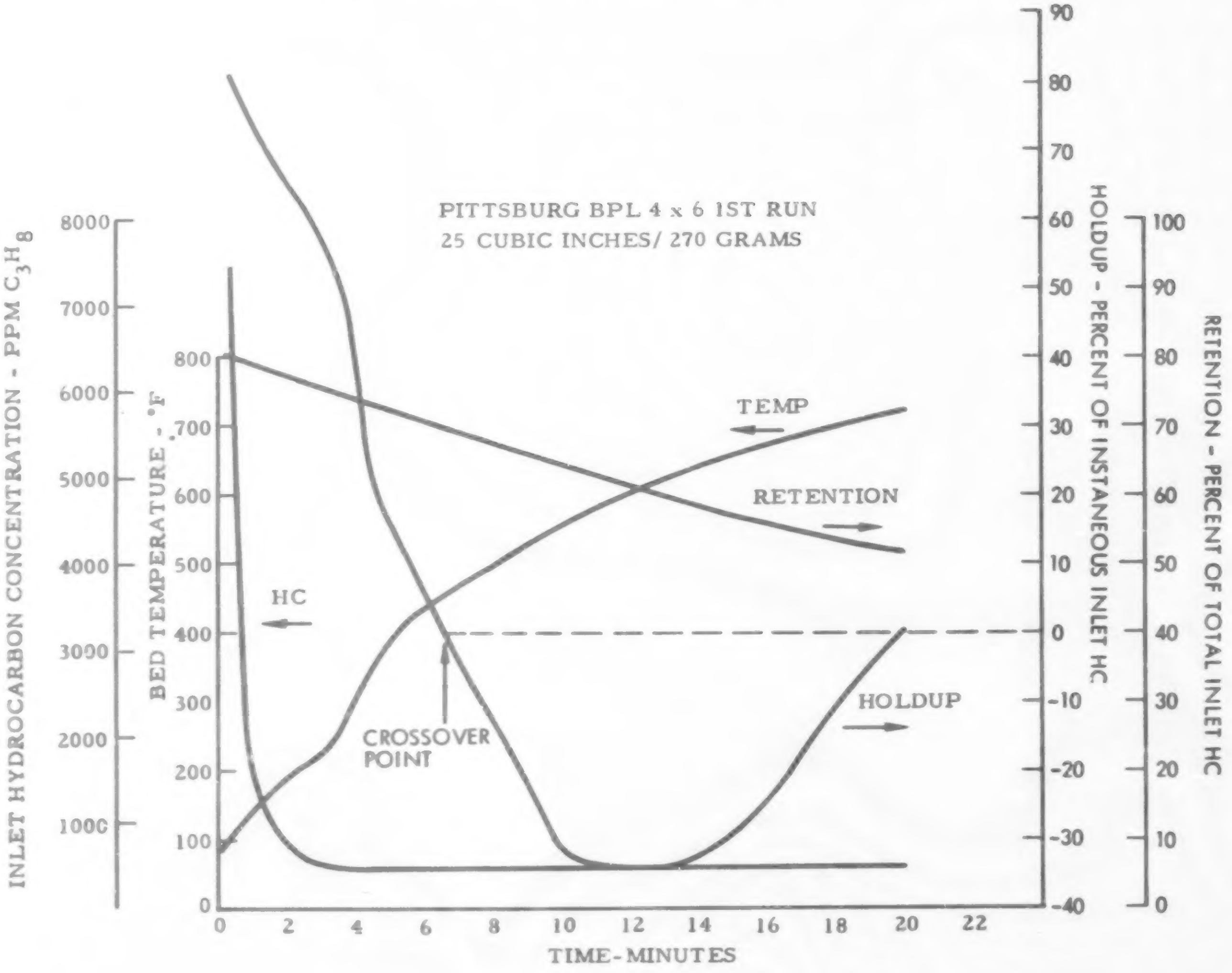
7.2.1 Discussion of Results

The criteria for selection of the two most promising adsorbents for utilization in the hydrocarbon accumulator device were the following:

- Temperature or time from engine start at which net hydrocarbon adsorption ceases to take place on the accumulator bed.
- Total hydrocarbons adsorbed prior to reaching crossover temperature.

FIGURE 7.3

TYPICAL TIME VARYING CHARACTERISTICS OF HYDROCARBON ACCUMULATOR MATERIAL SCREENING TESTS



- The extent of desorption and the temperature at which desorption starts. Note that crossover does not necessarily mean desorption has started, the latter is indicated when the total hydrocarbons within the bed begins to decrease.
- Mechanical and chemical stability of adsorbent material.
- Pressures drop across the device.

Attrition problems encountered during the tests arise from two sources: poor bed packing and the physical properties of the material. Many of the tests were performed during the "learning" period in which the packaging technique described previously was developed. It is therefore conceivable that some of the observed attrition could have been due to faulty packing. However, it is also probable that some of the attrition would have occurred under even ideal conditions. For example, silica gel breaks up into fines when it absorbs condensed water which is present in the cold exhaust stream. Fines were also observed to occur readily in the first charcoal tested and thus it was eliminated from further consideration. A more thorough testing might prove these eliminations unjustified; however, the objective of demonstrating the usefulness of the hydrocarbon accumulator was met with one of the materials tested after the packaging problem was apparently solved.

As a result of the screening tests, and allowing for packing variations, the accumulator materials can be ranked in order of decreasing physical stability:

- activated alumina pellets
- 13X molecular sieve cylinders
- 10A to 13X molecular sieve spheres
- activated carbons of the Pittsburgh BPL type
- nuclear activated carbons WV-H type
- silica gel
- coconut shell charcoal, Barnaby-Chaney MI 8588
- nut shell charcoal, Barnaby-Chaney KE 9948

The test procedure was satisfactory in providing fairly reproducible starting conditions, simulating actual engine starts. As would be expected, the largest HC concentration variation occurred during the first few seconds of engine operation due to variations in cranking speed, throttle opening, mixture induction and ambient conditions. However, since the exhaust flow rates were small during this period, the variation in the total inlet hydrocarbon mass from run to run is probably low. The data in Appendix I also shows that the percentage of hydrocarbons held by the accumulator material during the first 30 seconds depends more on the nature of the material than the absolute magnitude of HC concentrations.

Table 7.1 presents a summary of the complete data used to rank the adsorbents on the basis of all criteria. The first column describes the material tested, the second indicates the number of adsorption-desorption cycles performed on it. The next two columns show the crossover temperature and time. The fourth and fifth columns indicate the time intervals during the twenty minute test that desorption and adsorption took place, with the exception of the fifth run of the Pittsburgh BPL Activated Carbon which was subjected to special preconditioning which is described later. The next three columns present the mass of hydrocarbons retained during adsorption, the mass desorbed during desorption, and the quantity that could not be desorbed in the twenty minute cycle. Finally, the last column indicates the approximate cost of the tested accumulator candidates.

Evaluation of the tabulated data leads to the following conclusions:

- The maximum temperature at which adsorption takes place depends on the adsorbent used. It is a decreasing function of the order of listing of materials in Table 7.1.
- The quantity of retained hydrocarbons during adsorption increases with increasing crossover temperature.
- The time interval during which desorption occurs depends on the nature of the adsorbent, but not necessarily on the amount of adsorbed hydrocarbons.
- The amount of hydrocarbons retained by the adsorbent at the end of the adsorption-desorption cycle cannot be directly related to the quantity adsorbed prior to desorption.
- The apparent decrease in amount of hydrocarbons adsorbed during cycles subsequent to the first cycle is small when corrections in adsorption efficiency are made for material attrition. For example, the second and third runs of the charcoal and silica gel show roughly the same retention as the first run if the data is corrected for adsorbent weight loss.

TABLE 7.1
PERFORMANCE COMPARISON OF ACCUMULATOR MATERIALS

Type of Material	Adsorption-Desorption Cycle No. (Cold Start)	Crossover		Adsorption Time Interval (min)	Desorption Time Interval (min)	HC Retained During Adsorption Interval grams (lb)	Hydrocarbons Desorbed During Desorption Interval grams (lb)	Net HC Related During Cycle (grams)	Approx. Cost of Accumulator Material ($/lb.)	Remarks
		Temp. (°F)	Time (min)							
Activated Carbon Pittsburgh BPL Type 4x6 mesh	"as received"	430	6.0	6.0	14.0	2.1 ±0.1	0.6 ±0.05	1.5	0.45	no attrition
	2nd	465	7.0	7.0	13.5	1.5	0.6	1.0		
	3rd	385	5.0	5.0	14.5	1.7	0.7	1.0		
	4th	380	5.0	5.0	15.5	2.0	0.9	1.1		
	5th	195	2.5	2.5	23.5	1.6	8.5	7.5		
Nuchar WV-H 6x16 mesh	"as received"	355	4.5	4.5	5.0	1.7	0.2	1.5	0.50	15% attrition was observed
	2nd	345	5.0	5.0	8.5	2.5	0.1	2.4		
Coconut Shell Barneby-Cheney MI 8588 10x20 mesh	"as received"	470	8.0	8.0	0	2.8	0	2.8	3.0	there was no desorption observed in this run even at temp 700°F
	2nd	390	6.0	6.0	6.0	1.8	0.2	1.6		
	3rd	360	5.0	5.0	9.0	0.8	0.3	0.5		40% of bed was lost by end of 3rd run
Molecular Sieve Linde 13X 1/8x1/16" cylinders	"as received"	235	1.5	1.5	12.5	0.6	0.1	0.5	1.20	no attrition
	2nd	210-255	1.3	1.0	13.0	0.7	0.4	0.3		
Molecular Sieve Davidson 10A-13X 1/16" spheres	"as received"	310	3.5	3.0	4.5	1.0	0.1	0.9	2.25	approx. xero attrition
	2nd	195	2.0	2.0	6.0	1.0	0.2	0.8		

TABLE 7.1 (cont'd)
PERFORMANCE COMPARISON OF ACCUMULATOR MATERIALS

Type of Material	Adsorption-Desorption Cycle No. (Cold Start)	Crossover		Adsorption Time Interval (min)	Desorption Time Interval (min)	HC Retained During Adsorption Interval grams (lb)	Hydrocarbons Desorbed During Desorption Interval grams (lb)	Net HC Related During Cycle (grams)	Approx. Cost of Accumulator Material ($/lb.)	Remarks
		Temp. (°F)	Time (min)							
Silica Gel Davidson Grade 40 6x12 mesh	"as received"	-	-	-	-	-	-	-	-	very poor start for meaingful data
	2nd	175	1.5	1.5	12.5	1.5	0.6	0.9	2.20	12% attrition
	3rd	170	1.5	1.0	18.5	0.6	0.6	0		
Activated Alumina Harshaw 1/8x1/8" cylinders	"as received"	~120	<1.0	<1.0	4.0	1.0	0.2	0.8		no attrition

- Under the experimental test conditions it was impossible to desorb an amount of hydrocarbons equal to that retained during the adsorption segment of the test cycle. This holds true for all tested adsorbents, but the quantity of hydrocarbons retained at the end of the cycle depend on the nature of the adsorbent material as the next to the last column of Table 7.1 indicates.
- Chemical deterioration of the adsorbents was below detectability limits of the CO, CO_2 and O_2 monitoring equipment.
- Physical deterioration, attrition and erosion, were severe with some adsorbents, negligible with others. While the nature of the adsorbent plays an important role it is felt that proper packaging should eliminate this problem for most of the adsorbents. Small modifications in our original packing procedure, virtually eliminated physical degradation of the Pittsburgh activated carbon bed. For example initial tests showed about a 10% loss per cycle; after repackaging the loss was negligible. Additionally, pretreatment of the adsorbent, e.g., washing off fines, should help the integrity of the bed.

A question arises as to the validity of using only a few cycles to draw conclusions as to the constancy of adsorption efficiency and the ability to desorb the bed as it tends toward saturation due either to excessive exhaust HC in the cold period or repeated failure to desorb the bed.

To explore this situation we subjected the Pittsburgh BPL activated carbon to a further test. The engine was cold started and choke was left fully on for thirty seconds. The mixture enrichment was so severe that the engine was barely able to keep running at the end of the thirty seconds. The bed and engine were allowed to cool to ambient temperature and then the procedure was repeated for a total of four starts. The fifth start of Table 7.1 for the BPL activated carbon was made after these four fuel rich starts. An estimated 16 grams of HC were trapped in the bed, roughly equivalent to the HC bed inlet mass flow for 16 runs.

The crossover time and temperature of the fifth cold start were lower than those of the previous four test cycles, but the quantity of adsorbed hydrocarbons was within the range obtained during the earlier cycles. The material did not appear to become saturated prematurely, suggesting that complete bed desorption after each cold start may not be necessary for a satisfactory accumulator. The test indicates that the hydrocarbon accumulator may be suitable for controlling several cold start hydrocarbons even though the vehicle is not operated for long enough periods between cool down to insure full bed desorption.

The data in Table 7.1 was evaluated against the criteria for selecting hydrocarbon accumulator materials and the adsorbents were ranked in the following order of decreasing preference:

- activated carbon, Pittsburgh BPL
- activated carbon, Nuchar WV-H
- molecular sieve, Davidson 10A-13X
- molecular sieve, Linde 13X
- charcoals, nut shell
- activated aluminas
- silica gels

The first material, Pittsburgh BPL activated carbon, was selected as the bed material for a full size hydrocarbon accumulator to be used in conjunction with the full sized catalytic converter during the hybrid system emission tests. It exhibited sufficient adsorption capacity to insure it would trap and retain cold start hydrocarbons long enough to allow the catalytic converter to come up to a temperature where it could effectively treat the stored hydrocarbons. It showed good chemical and physical stability and it is an inexpensive material. Molecular sieves were selected as back-up candidates; however, their crossover temperatures and adsorption capacity may be marginal for a viable hydrocarbon accumulator. Further work is required to explore the usefulness of these materials.

8.0 CHARACTERIZATION OF TRW-HARSHAW THREE-COMPONENT CATALYST

8.1 Background of Three-Component Catalysis

Under ideal circumstances, the combustion of gasoline in an internal combustion engine (ICE) follows the equation:

$$C_x H_y + \frac{(4x + y)}{4} O_2 \rightarrow X\ CO_2 + \frac{y}{2} H_2O$$

A stoichiometric air-fuel mixture is one in which there is the correct amounts of air and fuel so that it would be possible for the above reaction to be completed with no fuel or oxygen left over.

However, even under stoichiometric conditions incomplete combustion, wall quenching effects and the combining of nitrogen and oxygen leave various other species in the exhaust stream; carbon monoxide, hydrocarbons, hydrogen, nitric oxide and oxygen. The general behavior of the exhaust of an ICE is such that:

- CO concentrations decrease approximately linearly with increasing air-fuel ratio up to stoichiometry. From there on they remain flat up to very lean mixtures where they increase again due to engine misfire and incomplete combustion.
- HC and H_2 concentrations generally follow the CO relationship; however, H_2 levels do not increase again at excessively lean mixtures.
- O_2 concentrations are relatively low and constant with increasing air-fuel ratio up to stoichiometry. Beyond that point they rise with increasing leaness.
- NO concentration levels rise with increasing air-fuel ratio reaching a peak around stoichiometry after which they fall approximately linearly with increasing air-fuel ratio.

Furthermore, the absolute and relative values of the concentrations are functions of engine design, fuel composition, throttle setting and timing.

Three-component catalysis in terms of automotive emission control refers to the process of simultaneously accelerating the oxidation of exhaust stream hydrocarbons and carbon monoxide and the reduction of nitric oxide. In effect, three-component catalytic conversion is a means by which the combustion equation is forced to completion outside the engine. The extent of reaction completeness depends on the chemical makeup of the exhaust stream and the ability of the catalyst to promote the following reactions:

$$CO + NO \rightarrow CO_2 + 1/2\ N_2$$

$$C_x H_y + \frac{(4x + y)}{2} NO \rightarrow XCO_2 + \frac{y}{2} H_2O + \frac{(4x + y)}{4} N_2$$

$$H_2 + NO \rightarrow H_2O + 1/2\ N_2$$

$$H_2 + 1/2\ O_2 \rightarrow H_2O$$

$$CO + 1/2\ O_2 \rightarrow CO_2$$

$$C_x H_y + \frac{(4x + y)}{4} O_2 \rightarrow XCO_2 + \frac{y}{2} H_2O$$

Inspection of the equations gives an insight into the nature of three-component catalysis. For rich mixtures where the concentration of O_2 is small compared with the NO concentrations, the first set of three equations would tend to dominate. The reduction of NO should be high and be relatively independent of air-fuel ratio as long as there are more total reductants (CO, HC and H_2) then there is NO.

On the other hand, at mixtures leaner than stoichiometry, the second set of equations becomes more important. The oxidation of H_2, CO and HC progresses quite rapidly as there is now an excess of oxidants (NO and O_2). However, NO reduction is forced to compete with O_2 for reductants, and depending on the relative dynamics of the chemical reactions may or may not compete favorably.

The above considerations lead to the conclusion that the conversion performance of a three-component catalyst will be influenced mainly by the mixture ratio in the engine as it affects the chemical composition of the exhaust gases.

There are several characteristics which are important for a practical catalytic converter besides having high conversion efficiencies over a reasonable mixture ratio:

- The catalytic reactions should become effective at low temperatures so as to minimize the time after engine start during which the emissions are uncontrolled.
- The reactions should approach completion at high space velocities so that the converters are "reasonably" sized.
- The catalyst should not produce any objectionable substances such as ammonia in side reactions over the normal operating regime for which it is designed.

- The catalyst should use low cost materials which should exhibit tolerance to fouling from gasoline additives such as sulfur and chlorine.
- The catalyst should be able to resist repeated thermal cycling and elevated temperatures.

8.2 Catalyst Preparation and Bench Scale Tests

The catalyst material furnished by Harshaw Chemical Company is composed of copper oxide on alumina pellets 1/8 inch in diameter by 1/8 inch long. The copper oxide loading is approximately 10% of the pellets' weight. The catalyst was activated by exposing the material to a reducing stream of CO and N_2 at elevated temperature for extended time periods. The catalyst was activated in two-pound batches after which it was tested for catalytic activity.

Bench scale evaluation was conducted using a small 1.2 cubic inch reactor containing the activated catalyst. The reactor was supplied with a synthetic mixture of gases simulating auto exhaust near stoichiometry. The synthetic exhaust used in the bench scale test had the following composition:

Carbon Dioxide--------------------12%
Water Vapor-----------------------12%
Methane---------------------------400-600 ppm
Carbon Monoxide-------------------1000-3000 ppm
Nitric Oxide----------------------500-800 ppm
Oxygen----------------------------1200 ppm
Balance---------------------------nitrogen

For each batch, the conversion efficiency of the catalyst, defined as the ratio of outlet concentration of a particular exhaust specie to the inlet concentration, was determined at several temperatures. In addition, the "light off" temperature, the temperature at which a specific conversion begins, was measured.

Steady state conversion results are shown in Table 8.1. The inlet reductant-oxidant concentrations are expressed as R/O ratio; reductants composed of CH_4 and CO, oxidants composed of NO and O_2. Note that each CH_4 is equivalent to three CO molecules in reducing power and each O_2 is equivalent to two NO molecules in oxidizing power.

TABLE 8.1

BENCH SCALE TESTS ON TRW-HARSHAW CATALYST

Reactor Bed Volume - 1.2 cubic inches
Space Velocity - 48,000 V/V/Hr at 1400°F

Temperature °F	R/O		Conversion (%)			
		CH_4	CO	NO	O_2	Remarks
1390 ± 20	1.05 ± 20	91 ± 3	100	89 ± 2	100	six samples
1390 ± 10	1.3	61	100	98	100	one sample
"	1.14	84.5	98	98	100	" "
"	1.07	88	100	88	100	" "
"	0.96	96.3	100	70	100	" "
"	0.93	98.7	100	65	100	" "
1215 ± 15	1.12 ± 02	70.0	98	50	100	" "
1335 ± 15		79.6	100	82.5	100	" "
1385 ± 10		85.0	100	85.0	100	" "
1465 ± 5		87.5	100	96.5	100	" "

The data suggested:

- The activation process would produce batches having similar conversion properties.
- The conversion of HC, CO and NO would be high at 1400°F and stoichiometric air-fuel ratios.
- The tolerance to air-fuel variations would be higher on the rich side of stoichiometry.

Conversion efficiencies measured at lower temperatures indicated the "light off" temperatures of the catalyst are approximately:

CO---------------------300°F
NO---------------------650°F (for stoichiometry)
500°F (rich mixtures)
CH_4--------------------1000°F

8.3 Evaluation of TRW-Harshaw Catalyst on Engine Exhausts

The TRW-Harshaw catalyst was characterized using the exhaust gas from one cylinder of the VW 1600 cc engine. Single cylinder testing was chosen to minimize the test bed size and to isolate effects of multi-cylinder air-fuel variations. Later the catalyst bed size was increased by a factor of four and the second converter was used and evaluated on the full exhaust flow of a larger displacement Chevrolet Vega engine.

8.3.1 Single Cylinder Catalyst Characterization Tests

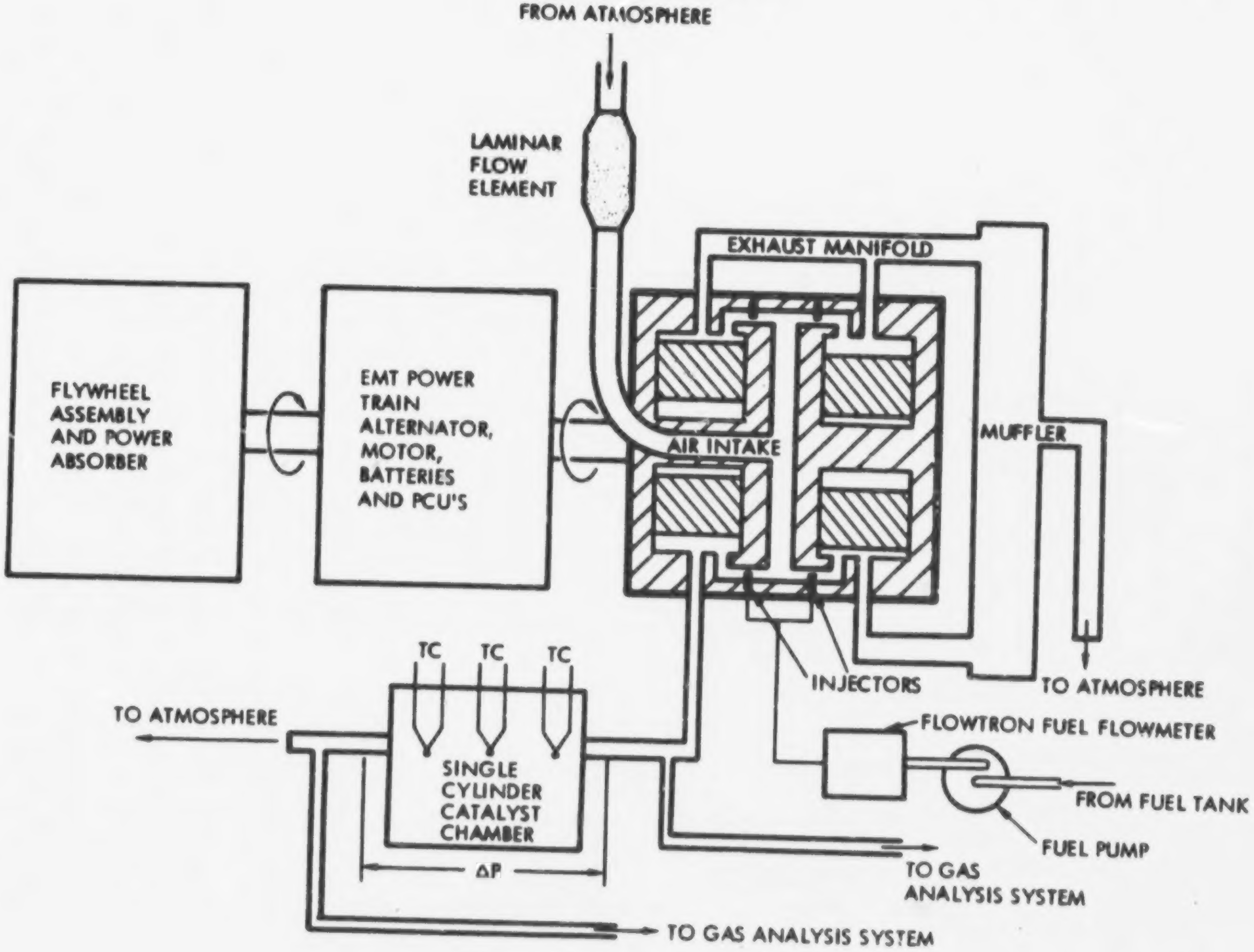
8.3.1.1 Test Equipment and Procedures

The experimental set-up for the single cylinder catalyst tests is represented in the block diagram of Figure 8.1.

The engine used was a 1968 Volkswagen 1600 cc engine equipped with electronically-controlled intake port fuel injection. The fuel injection control circuitry was modified in two ways. First, the control of the duration of each injection pulse was adapted so that the mixture ratio of the engine could be manually adjusted over a wide range from flooding to lean misfire. Secondly, the thermal transducer controlling the choking signal was added in its place so that the "choke" could be varied independently of engine thermal conditions. The engine throttle position was controlled by a small servo motor on the throttle linkage; throttle position was controlled independently of engine speed and air-fuel ratio. Engine timing was set according to manufacturer's specification. Engine speed was controlled by the EMT power train. The engine nominal speed was maintained at 1800 rpm independent of load conditions.

Air flow into the engine was monitored by using a Meriam Instrument Company laminar flow element (LFE) flowmeter scaled for 0-100 SCFM. Pressure drop across the LFE was read on a 0-10 inch H_2O, inclined manometer and recorded on a strip chart with a Statham Instruments 0-1 psid pressure transducer. Air temperature for the LFE corrections were read on a mercury-in-glass thermometer suspended near the air inlet to the engine. This installation did not guarantee that the true air temperature was read in the LFE and may have accounted for some of the variations in air-fuel ratio measurements discussed in Appendix J.

FIGURE 8.1
EXPERIMENTAL SET UP FOR SINGLE CYLINDER CHARACTERIZATION OF TRW-HARSHAW CATALYST


FROM ATMOSPHERE
LAMINAR FLOW ELEMENT
EXHAUST MANIFOLD
FLYWHEEL ASSEMBLY AND POWER ABSORBER
EMT POWER TRAIN ALTERNATOR, MOTOR, BATTERIES AND PCU'S
AIR INTAKE
MUFFLER
TC
TC
TC
INJECTORS
TO ATMOSPHERE
TO ATMOSPHERE
FLOWTRON FUEL FLOWMETER
SINGLE CYLINDER CATALYST CHAMBER
FROM FUEL TANK
FUEL PUMP
ΔP
TO GAS ANALYSIS SYSTEM
TO GAS ANALYSIS SYSTEM

Fuel flow was measured by a Flowtron Inc., Model 10 flowmeter, scaled for 0-10# fuel/hour. Fuel from a gasoline storage tank was pumped through the flowmeter and the fuel injectors by the VW fuel pump originally supplied with the engine. The complete fuel measuring system along with signal and strip chart amplifiers was calibrated in-situ using a catch and weigh technique.

Manifold pressure was monitored by a mercury vacuum manometer and was recorded on a strip chart by means of an absolute pressure transducer. Other conditions such as test cell temperature and atmospheric pressure were recorded daily or during each run.

Two gas analysis trains were used in the measurement of catalyst conversion effectiveness and HC accumulator screening. One system comprised a Scott Research Laboratories Model 108 Analysis System. That totally self-contained system included the following instruments:

Beckman Model 315A NDIR CO Analyzer
Beckman Model 315A NDIR CO_2 Analyzer
Beckman Model 315A NDIR NO Analyzer
MSA Total Hydrocarbon Analyzer
Beckman Model 715 Process Oxygen Analyzer
Sample pumps, traps, flowmeters, filters and strip chart recorders necessary for a complete on-line stream analysis.

The other gas analysis train was composed of an assembly of individual units including:

Beckman Model 315A NDIR CO Analyzer
Beckman Model 315A NDIR NO Analyzer
Beckman Model 400 FID HC Analyzer
Beckman Model 715 Process Oxygen Analyzer

Exhaust gas from the #4 cylinder flowed to the characterization canister through a short (~2 inch) exhaust pipe fitted to the exhaust pipe and then to the atmosphere. The exhaust of the other three cylinders flowed through the conventional VW muffler to the atmosphere.

The first canister built for catalyst evaluation was constructed of three major pieces. A central, removable wire basket 8" long x 7" wide x 2 1/2" deep, holding the catalyst bed was inserted into a thin-walled stainless steel jacket. Gas entered through a transition section in the 2 1/2 x 7" end, flowed diagonally across the bed and exited at the rear 2 1/2 x 7" transition section. This canister design was not satisfactory. The flat sides of the canister bowed due to thermal distortion. The flanges and gasket area of the transition and jacket were difficult to mate properly and the flange material was oxidized and burned out. The orientation of the container (7" width vertical, long dimension horizontal), coupled with shaking motions induced by the engine and the high flexibility of the wire basket repeatedly caused the bed to settle, resulting in a poor flow distribution. The NO conversion of this canister never exceeded 50%.

A new canister was constructed to eliminate many of the problems of the original design. This canister was also designed so that it could be used for the hydrocarbon accumulator material screening tests described in Section 7. The canister which was shown schematically in Figure 7.1, consisted of a double walled cylindrical vessel. The inner diameter of the canister was about 5 inches. The catalyst was positioned between retainer screens separated by about 6 1/2 inches. During the final emission tests using the Vega engine, the canister was filled with 6 1/2 inches of the selected accumulator material. The pressure drop across the 6 1/2 inch deep bed filled with the TRW-Harshaw catalyst was about 3 inches of water at the highest tested space velocity of 37,000 V/V/Hr.

8.3.1.2 Single Cylinder Catalyst Characterization Results

Steady State Catalyst Conversion Efficiencies

Table 8.2 presents the steady state data obtained from the single cylinder tests. The data is grouped into four sections with each section representing data derived from tests made at essentially constant temperature and space velocity. The first three columns of the table, following the "test number" column, indicate engine parameters at 1800 rpm; the next four list the pollutant and oxygen concentrations of the engine exhaust as a function of air-to-fuel ratio.

TABLE 8.2
TRW-HARSHAW COPPER CATALYST DATA

ENGINE PARAMETERS AND EXHAUST COMPOSITION											CATALYTIC DEVICE OUTPUT AND EFFICIENCY									
											HC as C_3		CO		NO		OXYGEN			
Test Nos.	Manifold Pressure "Hg	Engine Air Flow SCFM	Air-Fuel	HC as C_3 (ppm)	CO (%)	NO (ppm)	O_2 (%)	Reductant Concen (%)	Oxidant Concen (%)	R/O (ppm)	R/O	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Ave. Cat. Temp °F	Space Velocity V/V/Hr
1.1	7.20	7.5	13.15	385	4.40	1050	0.15	4.75	0.45	43,000	10.55	250	35.0	31,000	29.5	55	94.8	700	53.3	1220	28,000
1.2	7.13	7.8	14.55	425	2.30	1640	0.20	2.68	0.56	21,000	4.76	400	6.0	14,000	38.3	100	93.9	100	95.0	1210	↓
1.3	7.45	7.8	14.69	320	2.10	1620	0.18	2.39	0.52	18,700	4.60	280	12.5	10,000	52.4	110	93.2	350	80.6	1210	
1.4	7.40	7.8	14.72	350	1.70	2000	0.19	2.01	0.58	14,300	3.47	273	21.6	6,400	62.0	90	95.5	100	94.7	1210	
1.5	7.18	7.8	14.77	350	1.50	1930	0.22	1.81	0.63	11,800	2.87	295	16.0	5,700	62.3	55	97.2	200	90.9	1210	
1.6	7.10	7.9	14.78	360	1.75	1850	0.22	2.07	0.62	14,500	3.34	225	29.5	3,800	68.4	170	91.3	250	88.6	1230	
1.7	7.05	7.8	14.93	320	1.20	1950	0.23	1.49	0.64	8,400	2.33	290	19.5	6,100	65.2	175	90.5	200	91.1	1240	
1.8	7.33	7.8	15.08	280	1.30	1900	0.20	1.55	0.59	9,600	2.63	197	29.6	3,600	72.3	75	96.0	100	95.0	1220	
1.9	7.10	7.9	15.15	250	0.90	2000	0.25	1.12	0.70	4,200	1.60	145	32.0	1,700	81.0	165	91.7	300	88.0	1245	
1.10	7.35	7.8	15.18	230	1.13	2000	0.22	1.33	0.64	6,900	2.08	142	38.4	2,200	82.1	70	96.5	100	95.5	1230	
1.11	6.71	7.9	15.20	200	0.83	2150	0.30	1.01	0.83	1,800	1.22	78	61.0	500	94.1	80	96.3	200	93.3	1240	
1.12	7.20	7.8	15.30	190	0.80	2180	0.35	0.97	0.92	500	1.05	80	58.0	550	93.1	45	97.9	200	94.3	1230	
1.13	6.85	8.1	15.38	220	0.70	2250	0.31	0.90	0.84	600	1.07	43	80.5	250	96.4	140	93.8	400	87.0	1250	
1.14	7.10	7.9	15.40	150	0.58	2200	0.28	0.71	0.78	-700	0.91	38	74.7	200	96.5	200	90.9	200	92.9	1250	
1.15	6.85	7.9	15.45	160	0.55	2200	0.31	0.69	0.84	-1500	0.82	37	76.9	180	96.7	310	85.9	300	90.3	1235	
1.16	7.10	7.9	15.45	130	0.50	2100	0.32	0.62	0.85	-2300	0.73	25	80.8	130	97.3	620	70.5	800	75.0	1240	
1.17	7.20	7.9	16.03	180	0.55	2280	0.53	0.71	1.29	-5800	0.55	30	83.4	70	98.7	730	68.0	700	86.8	1250	
1.18	7.29	8.2	16.18	31	0.22	1900	0.43	0.25	1.05	-8000	0.24	2	93.5	50	98.8	1620	14.8	3,300	20.9	1225	
2.1	7.10	8.1	14.50	385	2.10	1940	0.22	2.45	0.63	18,200	3.89	290	24.5	10,000	52.4	260	86.6	300	86.4	1370	32,000
2.2	7.10	8.0	14.55	400	1.87	1950	0.25	2.23	0.70	15,300	3.19	240	40.0	9,000	51.9	60	96.9	250	90.0	1370	↓
2.3	7.20	7.7	14.60	390	1.60	2050	0.21	1.95	0.62	13,300	3.12	205	47.5	7,600	52.5	140	93.2	200	90.4	1400	
2.4	7.10	8.0	14.75	360	1.83	2020	0.33	2.15	0.86	12,900	2.50	155	57.0	3,050	83.4	175	91.3	500	93.4	1375	

TABLE 8.2 (cont'd)
TRW-HARSHAW COPPER CATALYST DATA

ENGINE PARAMETERS AND EXHAUST COMPOSITION												CATALYTIC DEVICE OUTPUT AND EFFICIENCY									
												HC as C_3		CO		NO		OXYGEN			
Test Nos.	Manifold Pressure "Hg	Engine Air Flow SCFM	Air-Fuel	HC as C_3 (ppm)	CO (%)	NO (ppm)	O_2 (%)	Reductant Concen (%)	Oxidant Concen (%)	R/O (ppm)	R/O	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Ave. Cat. Temp °F	Space Velocity V/V/Hr
2.5	7.10	8.0	14.95	325	1.35	2070	0.30	1.64	0.81	8,300	2.04	150	53.8	4,800	64.4	40	98.1	200	93.3	1390	32,000
2.6	7.00	8.0	15.05	290	1.28	2200	0.32	1.54	0.86	6,800	1.79	130	55.0	3,900	69.6	30	98.6	300	90.3	1390	↓
2.7	7.00	8.0	15.10	230	1.10	2280	0.35	1.31	0.93	3,800	1.41	115	50.0	1,950	82.2	240	89.5	350	90.0	1365	
2.8	7.20	7.7	15.20	215	0.95	2200	0.23	1.14	0.68	4,600	1.68	120	44.0	2,800	70.5	165	92.5	200	90.9	1385	
2.9	7.10	7.9	15.23	220	0.92	2100	0.23	1.12	0.67	4,500	1.67	65	70.5	2,100	77.2	35	98.3	300	88.0	1410	
2.10	7.00	8.0	15.65	180	0.90	2300	0.40	1.06	1.03	300	1.03	18	90.0	140	98.4	70	97.0	250	97.3	1410	
2.11	7.00	8.0	15.85	190	0.70	2300	0.48	0.87	1.19	-3,200	0.73	12	93.7	60	99.1	320	86.1	500	89.6	1400	
2.12	7.00	8.0	15.95	175	0.65	2380	0.45	0.81	1.14	-3,300	0.71	20	88.6	125	98.1	85	96.4	400	91.1	1400	
2.13	7.20	7.8	16.23	155	0.62	2300	0.41	0.76	1.05	-2,900	0.72	15	90.3	70	98.8	265	88.5	300	92.6	1380	
2.14	7.00	8.1	16.40	130	0.59	2450	0.60	0.71	1.44	-7,300	0.49	13	90.0	120	98.0	1320	46.2	1400	76.6	1375	
2.15	7.00	8.0	16.45	80	0.35	2480	0.68	0.42	1.61	11,900	0.26	5	93.8	20	99.4	1700	31.3	3000	55.8	1380	
2.16	7.00	8.1	17.20	70	0.17	2450	1.30	0.23	2.84	26,100	0.08	2	97.0	30	98.2	1320	46.2	4500	65.4	1390	
3.1	7.10	7.8	14.70	405	1.85	1750	0.19	2.21	0.55	16,600	3.99	135	66.6	11,400	38.5	40	97.7	50	97.7	1550	33,000
3.2	7.10	7.8	14.90	355	1.55	1850	0.21	1.94	0.60	13,400	3.23	93	73.8	8,300	46.5	25	98.6	100	95.2	1560	↓
3.3	7.10	7.8	15.19	260	1.02	2000	0.24	1.25	0.68	5,700	2.31	50	80.8	3,700	63.7	10	99.5	100	95.8	1565	
3.4	7.40	7.8	15.30	80	0.75	2300	0.28	0.82	0.79	300	1.04	20	75.0	600	92.0	100	95.7	20	99.3	1590	
3.5	7.10	7.9	15.37	160	0.67	2100	0.29	0.81	0.79	300	1.03	10	93.7	150	97.8	40	98.1	200	93.1	1575	
3.6	7.40	7.9	15.50	60	0.60	2250	0.30	0.65	0.82	-1,700	0.79	2	100.0	170	97.2	100	95.5	100	96.7	1590	
3.7	7.15	7.8	15.60	125	0.52	2100	0.29	0.63	0.79	-1,600	0.80	5	96.0	160	96.9	200	90.5	100	96.6	1570	
3.8	7.40	7.8	15.70	60	0.55	2380	0.35	0.60	0.94	-3,400	0.64	2	100.0	75	98.6	400	83.2	N.A.	--	1550	
3.9	7.40	7.8	16.00	50	0.65	2300	0.30	0.69	0.83	-1,400	0.84	2	100.0	50	99.2	700	69.6	300	90.0	1550	
3.10	7.35	7.8	16.45	45	0.20	2320	0.63	0.60	1.50	-9,000	0.40	2	100.0	60	97.0	280	88.0	400	93.7	1550	

TABLE 8.2 (cont'd)
TRW-HARSHAW COPPER CATALYST DATA

ENGINE PARAMETERS AND EXHAUST COMPOSITION												CATALYTIC DEVICE OUTPUT AND EFFICIENCY									
												HC as C_3		CO		NO		OXYGEN			
Test Nos.	Manifold Pressure "Hg	Engine Air Flow SCFM	Air-Fuel	HC as C_3 (ppm)	CO (%)	NO (ppm)	O_2 (%)	Reductant Concen (%)	Oxidant Concen (%)	R/O (ppm)	R/O	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Concen (ppm)	Conver (%)	Ave. Cat. Temp °F	Space Velocity V/V/Hr
4.1	4.43	8.8	14.30	445	2.50	1630	0.14	2.90	0.44	24,600	6.55	335	24.8	15,000	40.0	180	89.0	200	85.7	1380	37,000
4.2	4.10	8.8	14.55	410	2.10	2100	0.28	2.47	0.77	17,000	3.21	295	28.0	12,200	42.0	230	89.1	500	82.0	1440	↓
4.3	4.38	9.8	14.90	315	1.40	2075	0.20	1.68	0.61	10,700	2.75	225	28.5	7,200	48.5	220	89.4	250	87.5	1380	
4.4	4.10	9.8	14.90	370	1.70	2300	0.33	2.03	0.89	11,400	2.28	197	47.0	4,750	72.0	210	91.1	500	84.9	1460	
4.5	4.23	8.9	15.18	240	1.00	2150	0.24	1.22	0.70	5,200	1.75	150	37.5	4,100	59.0	210	90.2	300	87.5	1390	
4.6	4.05	9.6	15.20	330	1.35	2500	0.38	1.65	1.01	6,400	1.63	98	70.0	1,700	87.5	185	92.6	500	86.9	1455	
4.7	4.30	8.8	15.35	130	0.60	2350	0.27	0.72	0.78	-600	0.92	53	59.4	1,800	70.0	135	94.3	100	96.3	1395	
4.8	4.30	8.9	15.55	100	0.53	2300	0.28	0.62	0.79	-1,700	0.78	12	88.0	120	97.7	540	76.5	500	81.5	1395	
4.9	4.00	9.6	15.60	200	0.68	2900	0.57	0.86	1.43	-5,700	0.60	20	90.0	100	95.2	2050	29.0	1900	96.7	1430	
4.10	4.25	8.9	15.85	73	0.40	2420	0.35	0.47	0.94	-4,700	0.49	8	89.0	40	99.0	1270	47.5	N.A.	--	1360	
4.11	4.00	9.7	15.95	160	0.48	2850	0.75	0.62	1.78	11,600	0.35	16	90.0	70	95.5	2050	28.0	1000	86.7	1425	
4.12	4.05	9.6	16.10	105	0.30	2980	1.00	0.39	2.23	18,400	0.17	5	95.0	40	96.6	2250	24.5	6000	40.0	1410	
4.13	4.05	9.6	16.50	95	0.17	2850	1.35	0.26	2.98	27,300	0.09	5	95.5	20	98.8	2300	20.0	6000	55.6	1440	

Columns 9 through 12 indicate the engine exhaust reductants in CO equivalents, the total oxidants in NO equivalents and the difference and ratio of these two quantities. While hydrogen is also a reductant it was not measured during these tests since a cursory literature survey suggested that concentrations of this component of the exhaust would be small in comparison to the other reductants present at near-stoichiometric air-fuel ratios. Later, the hydrogen levels from the Vega engine were measured as discussed in Section 8.4 and it was shown that the hydrogen level from that engine could represent a substantial portion of the reductant makeup.

The rest of the columns indicate; the composition of the exhaust downstream of the catalyst, the catalytic conversion efficiencies of the four components of interest, the average catalyst temperature and the actual bed space velocity for each test. Three significantly different temperatures and space velocities were used. The air-fuel ratio extremes differed by as much as 30% of the apparent stoichiometric point*--the measured A/F ranged from 13 to 17.

Figures 8.2, 8.3, 8.4 and 8.5 present plots of the tabulated data. Examination of these curves and Table 8.2 leads to the following observations:

- The catalyst is generally non-selective in promoting the reaction of exhaust components. Comparison of the conversion efficiencies of the competing species (hydrocarbons vs. CO, and oxygen vs. NO) obtained from the approximately one hundred steady state test points do not indicate significant differences. At lower temperatures (∿1200°F) the CO oxidation appears to be favored over hydrocarbon oxidation while the opposite is true at temperatures above 1500°F. This effect however may be due more to "chemical thermodynamics" such as competition of the water-gas reaction and/or increased CO_2 dissociation than catalyst selectivity. The ratio of NO conversion to O_2 conversion increases very slightly with temperature; however it may be due to the other reasons suggested for the CO-HC shift.

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*Appendix J presents a discussion of the methods used for determining the stoichiometric air-fuel ratio in the single cylinder tests and later tests on the full flow of the Vega.

FIGURE 8.2
TRW-HARSHAW CATALYST CONVERSION EFFICIENCY
28,000 V/V/Hr; 1230±20°F

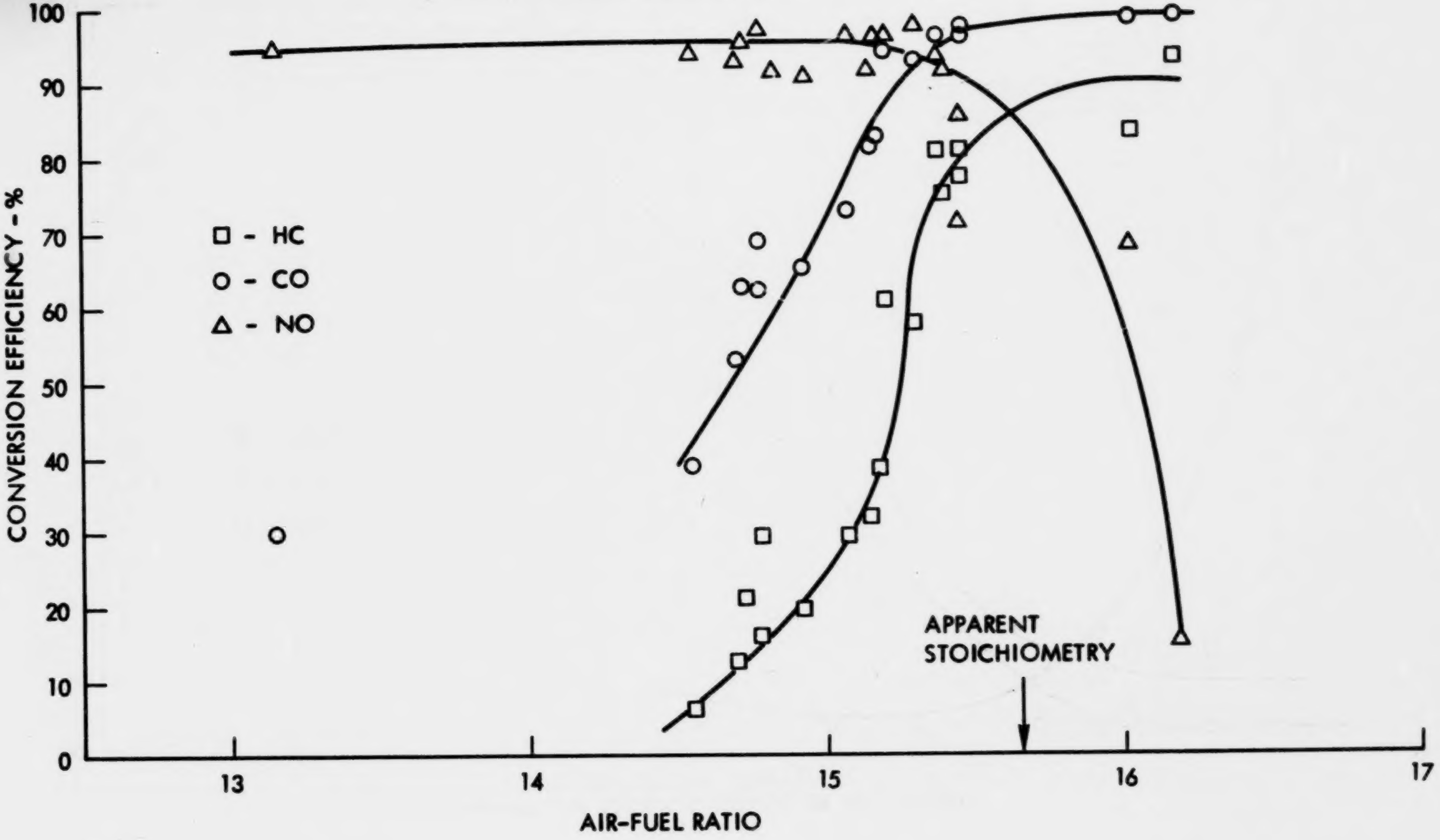


FIGURE 8.3
TRW-HARSHAW CATALYST CONVERSION EFFICIENCY
32,000 V/V/Hr; 1390±20°F

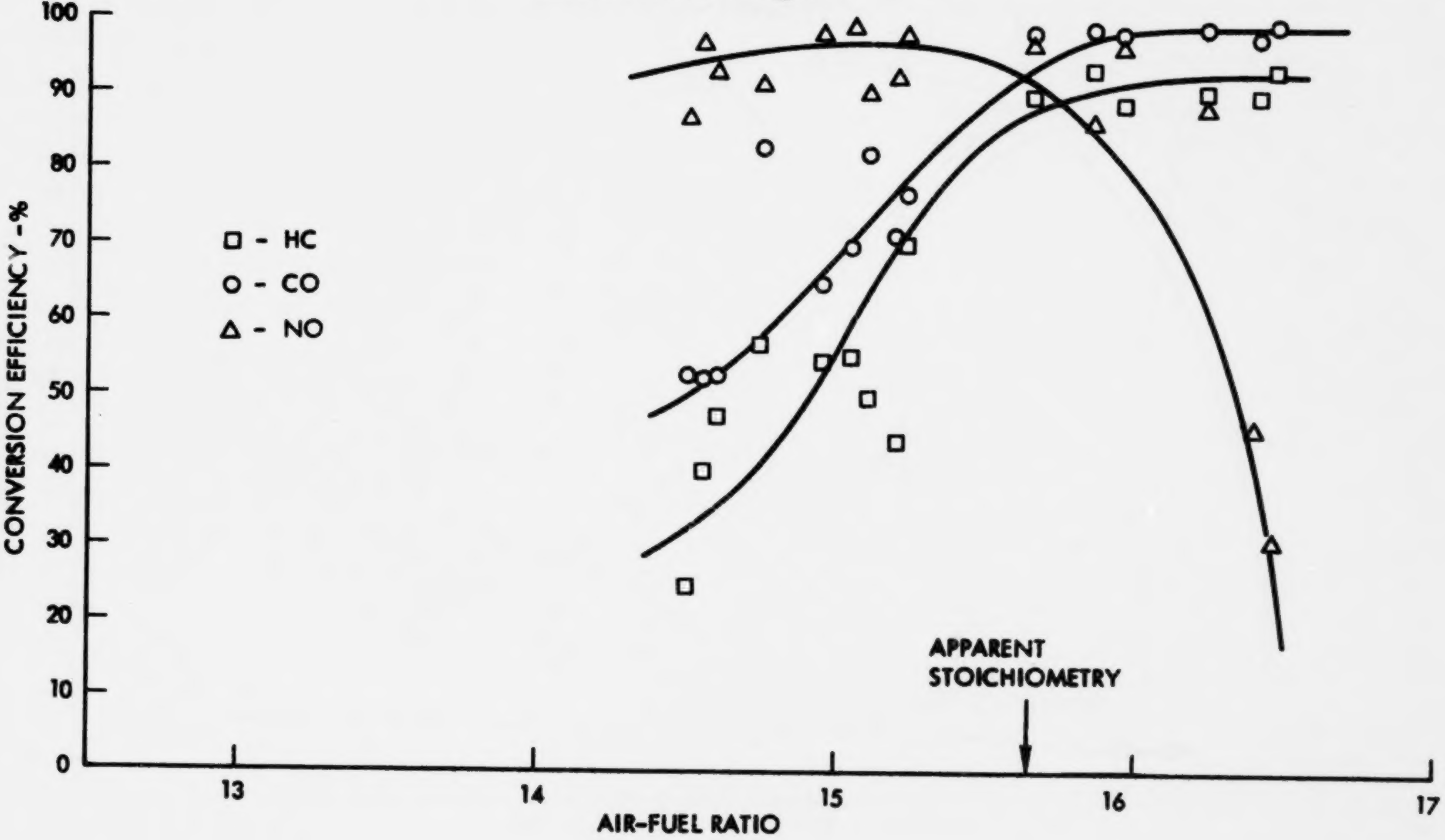


FIGURE 8.4
TRW-HARSHAW CATALYST CONVERSION EFFICIENCY
37,000 V/V/Hr; 1410±50°F

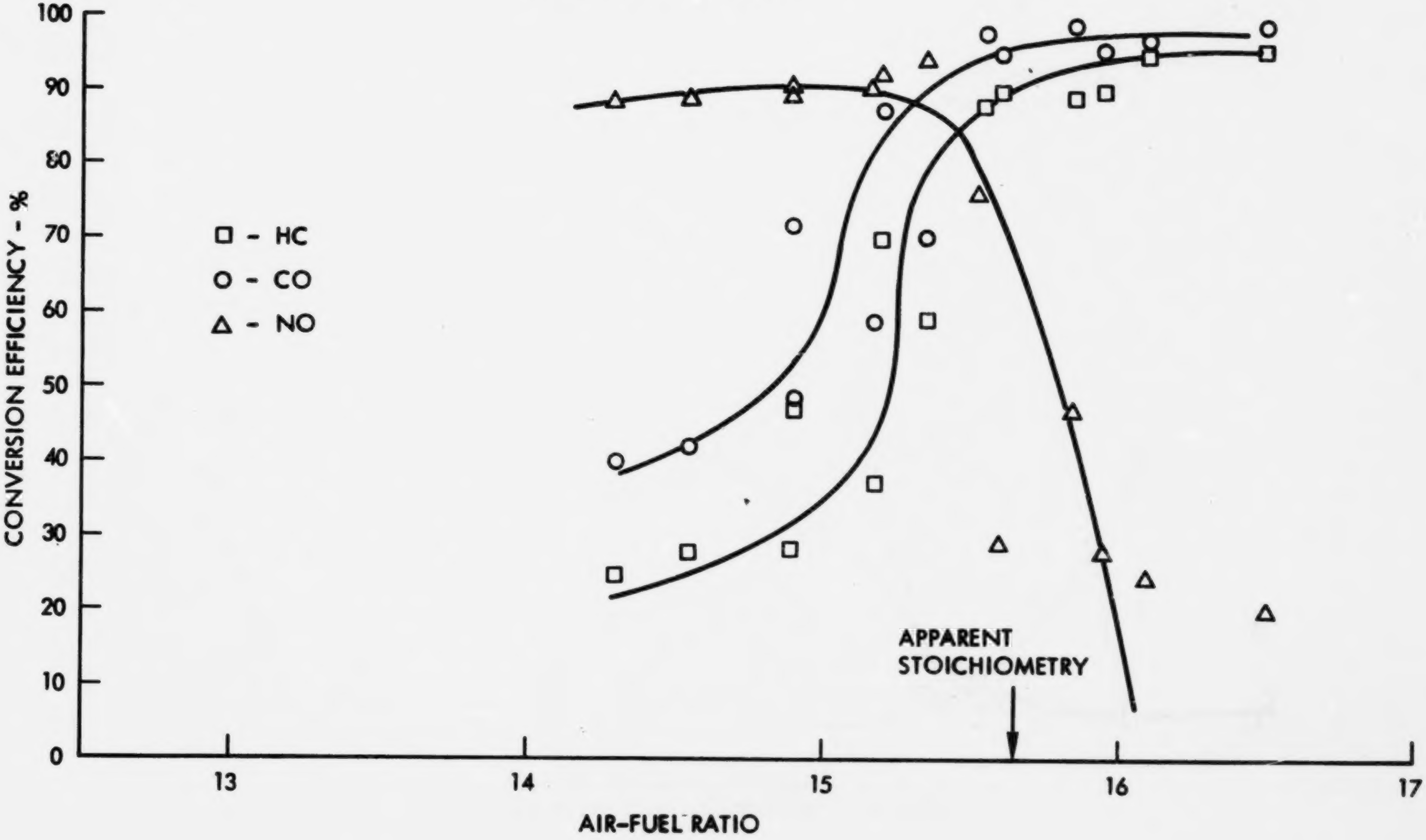
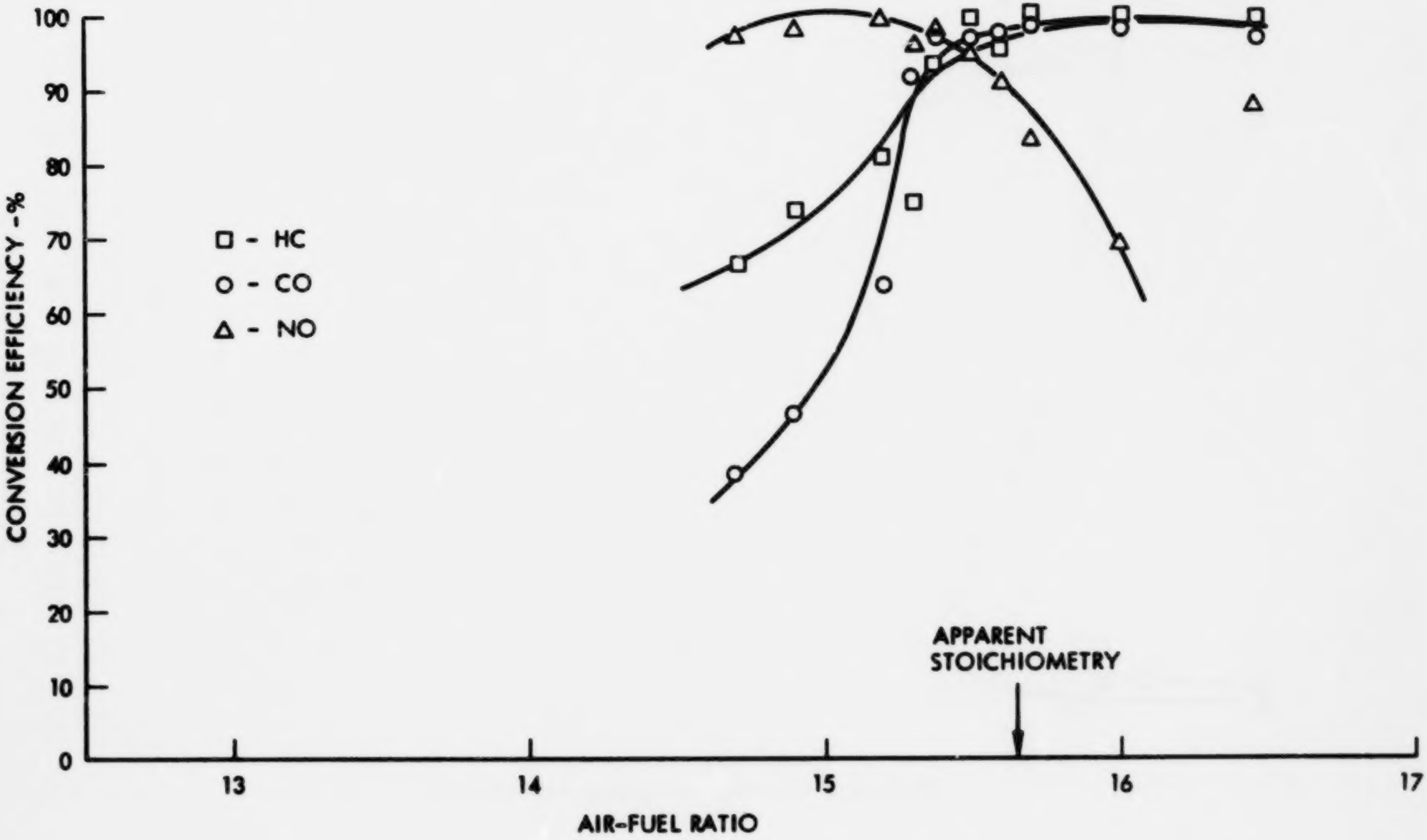


FIGURE 8.5
TRW-HARSHAW CATALYST CONVERSION EFFICIENCY
33,000 V/V/Hr; 1565±20°F



- The catalyst appears to be highly efficient in simultaneously reducing NO and O_2 and oxidizing CO for all space velocities as long as the air-fuel ratio does not vary by more than one A/F point. Hydrocarbon oxidation is high (>80%) as long as the bed temperature is above 1350°F. The maximum range of air-fuel ratios for which the simultaneous conversion of all three species exceeds 75% lies between 15.3 and 16.05; under most test conditions the A/F range is smaller.
- The relative conversion of the pollutants is temperature dependent. Comparison of Figures 8.2, 8.3 and 8.5 demonstrates this effect in terms of HC and CO. It can be seen that the temperature effect on conversion of those species is not linear with temperature; the conversion in the range between 1200 and 1400°F increases at a much faster rate with temperature than it does in the range from 1400 to 1600°F. Thus, operation of the catalyst at temperatures above 1400°F may be unnecessary for HC and CO control.
- Temperature effects become more pronounced when the three pollutants are viewed as a group. If, for example, it is necessary that the hot exhaust conversion of all pollutants reach 80% to meet the 1975-76 standards for a particular engine, then the allowable air-fuel ratio range is 0.7 air-fuel ratio points, or about 5% A/F of stoichiometry at 1390°F and 1565°F, but only 0.3 points at 1230°F. The allowable A/F range shrinks to a single-point value if the simultaneous conversion requirement is raised to:

    - 86% at 1230°F
    - 90% at 1390°F
    - 94% at 1565°F

  A precise set of conversion requirements cannot be set a priori because they will depend on the engine type, cold start properties and the existence of other emission controls such as exhaust recirculation, hydrocarbon accumulators, etc. In fact, in all probability the required conversions are not the same for each pollutants and a careful assessment of the probable exhaust signatures must be made before establishing an A/F range or temperature requirement.
- Space velocity had an effect on individual pollutant conversion. Increasing space velocity from 32,000 to 37,000 V/V/Hr at stoichiometry reduced the NO conversion from about 90% to 70% at around 1400°F. CO and HC conversions were only slightly affected under these conditions. On the other hand CO and HC conversions become space velocity sensitive at richer mixtures.
- The effect of air-fuel ratio variation is large outside of the narrow range specified by allowable temperatures, space velocities and the required conversions. On the rich side of stoichiometry reductant oxidation is limited by chemistry in terms of the lack of oxidizing species. On the lean side of stoichiometry reductant oxidation is complete but NO_x

reduction is limited by the overwhelming presence of oxygen and the possibility of catalyst oxidation, that is, the reversible catalyst poisoning by oxidation. If the apparent stoichiometric air-fuel ratio of 15.65 for the VW engine is correct, the allowable A/F variation is symetrical about stoichiometry at temperatures above 1350°F. At 1230°F and for pollutant conversion greater than 80% the allowable variation in engine A/F is only on the rich side of stoichiometry. Thus, it appears that the point of maximum simultaneous conversion of the three pollutants moves to leaner air-to-fuel ratios with temperature.

Non-Steady Effects

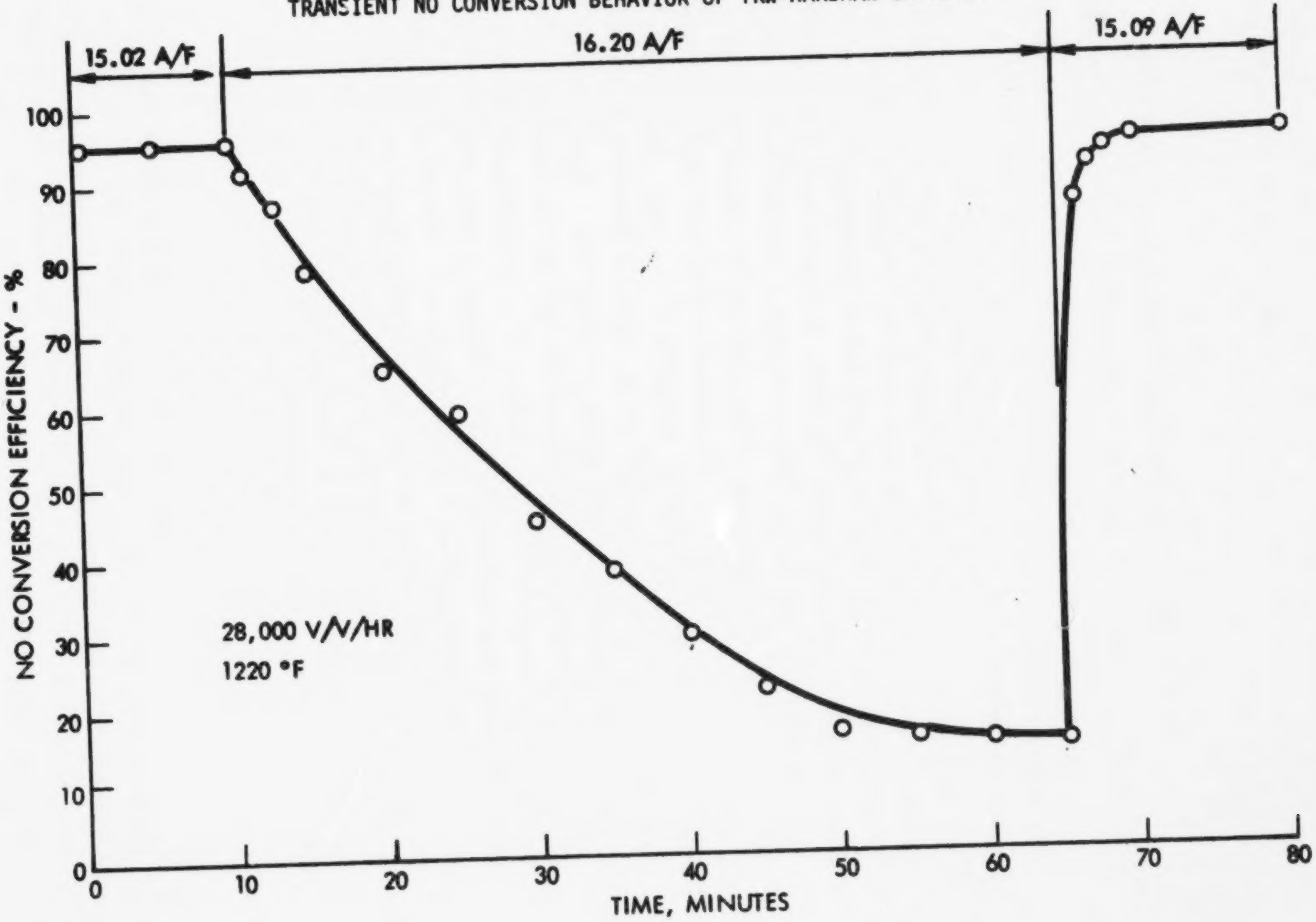
The data of Table 8.2 was gathered under steady state conditions defined as operation of the system at constant air-fuel ratio and mass flow for 15 minutes or more. The data for some of the slightly lean mixtures was measured for as long as 30 minutes. There is no guarantee that the measured high NO conversion data at mixtures leaner than stoichiometry would remain constant indefinitely; however if catalytic activity deterioration does take place it is extremely slow such that it is hardly discernible over the measurement period.

Short time duration excursions on the order of a few minutes to very lean mixtures can be tolerated by the catalyst in the space velocity range of these experiments. Figure 8.6 shows how the NO conversion varies in time with mixture step changes from rich to lean and back to rich. In the particular case shown the catalyst required 10 minutes for the NO conversion to fall to about 70% of its original level. Furthermore, the data reveals that a return to richer-than-stoichiometric mixtures restores the catalytic activity toward NO reduction almost immediately. Additional data, not shown here, on both VW and Vega exhausts indicated that the rate of catalytic activity restoration increases with an increase in temperature and decrease in A/F. Restoration is slow if a lean exhaust is changed to stoichiometric exhaust, but fast if the change is to a rich exhaust.

Physical Changes

Catalyst sintering, erosion and/or attrition was negligible in the single cylinder tests. The catalyst bed remained tightly packed during the entire test period spanning one month. In addition, the catalyst showed no catalytic activity deterioration even though it was subjected

FIGURE 8.6
TRANSIENT NO CONVERSION BEHAVIOR OF TRW-HARSHAW CATALYST



repeatedly to both extremely rich and lean exhaust mixtures; to engine misfire, to condensed moisture and to engine particulates (mainly carbon).

8.3.2 TRW-Harshaw Characterization Tests on Vega Engine

8.3.2.1 Full Scale TRW-Harshaw Catalytic Converter

A full scale catalytic converter was designed and tested on the exhaust stream of a 1971 Chevrolet Vega engine. The engine was modified in several ways as described in Appendix K.

The catalytic converter used in the tests was sized on the basis of the previous single cylinder test results. A schematic diagram of the converter is to be found in Figure 8.7 and a photograph of the disassembled converter and catalyst is shown in Figure 8.8. The converter was constructed of thin walled stainless steel; the bed diameter was 8 inches and it was 8 inches deep. Flow through the bed was from top to bottom as shown in Figure 8.6. Perforated plates were used on the inlet side to present a uniform flow distribution to the bed. Radial vane bed supports welded to the outlet wall of the canister provided stiffness and support of the bed's weight and static pressure drop. Approximately 3/4 inches of refractory insulation covered the cylindrical portion of the canister; this in turn was wrapped with a light aluminum jacket to provide support for the insulating jacket. Chromel-Alumel thermocouples were placed within the bed as shown in Figure 8.7 The bed was filled with approximately 6300 grams of freshly activated TRW-Harshaw catalyst. The converter was vibrated like the hydrocarbon accumulator during catalyst fill to settle the bed as much as possible and then the top retaining screen was screwed down to preload the bed in compression.

8.3.2.2 Steady State Test Results

Figures 8.9 and 8.10 present steady state data on the efficiency of the full scale TRW-Harshaw catalytic converter for controlling pollutants emitted from the Vega engine operated at a number of air-fuel ratios. The data was obtained at two exhaust flowrates and two catalyst temperatures.

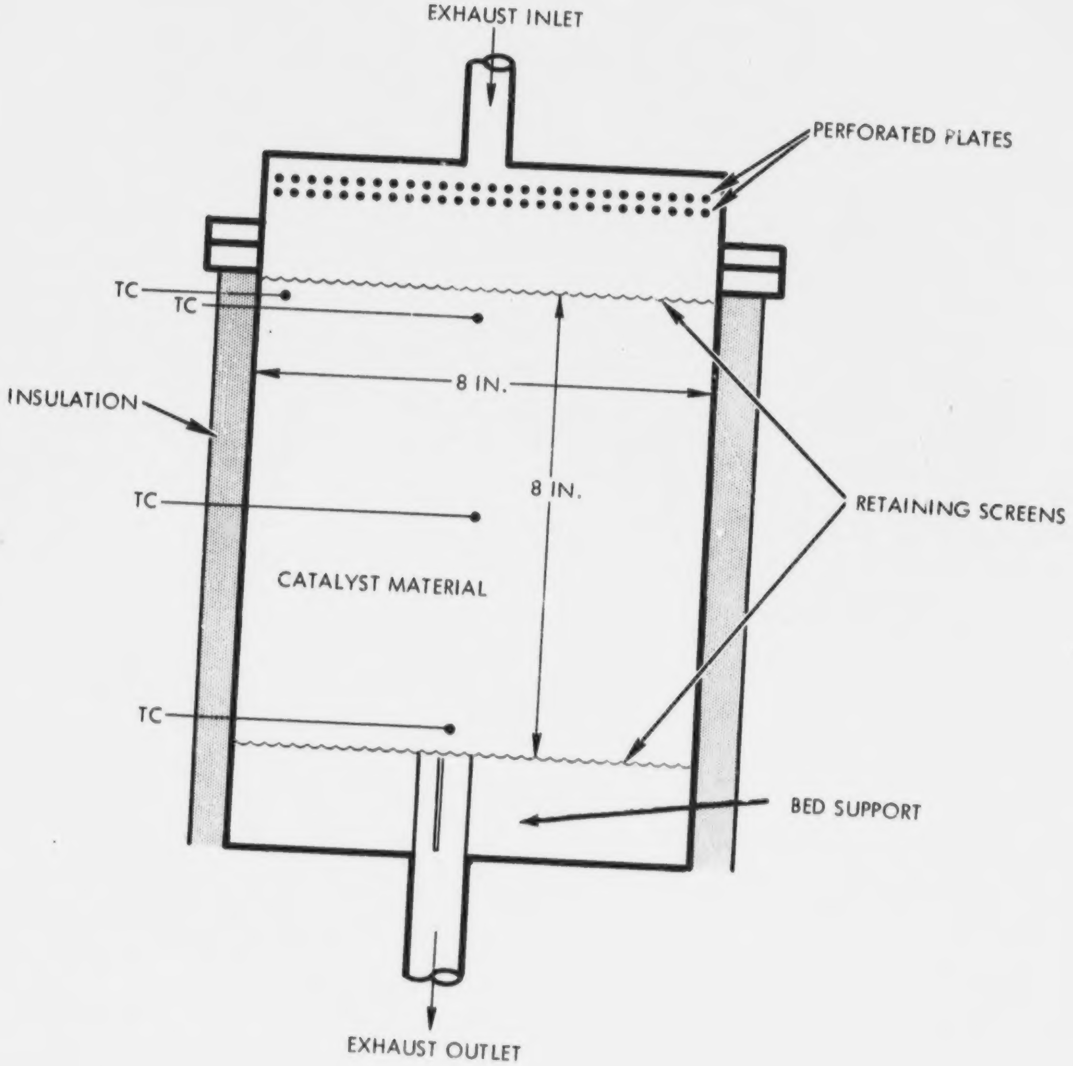

EXHAUST INLET
PERFORATED PLATES
TC
TC
INSULATION
8 IN.
8 IN.
TC
RETAINING SCREENS
CATALYST MATERIAL
TC
BED SUPPORT
EXHAUST OUTLET

FIGURE 8.7
FULL SCALE TRW-HARSHAW CATALYTIC CONVERTER

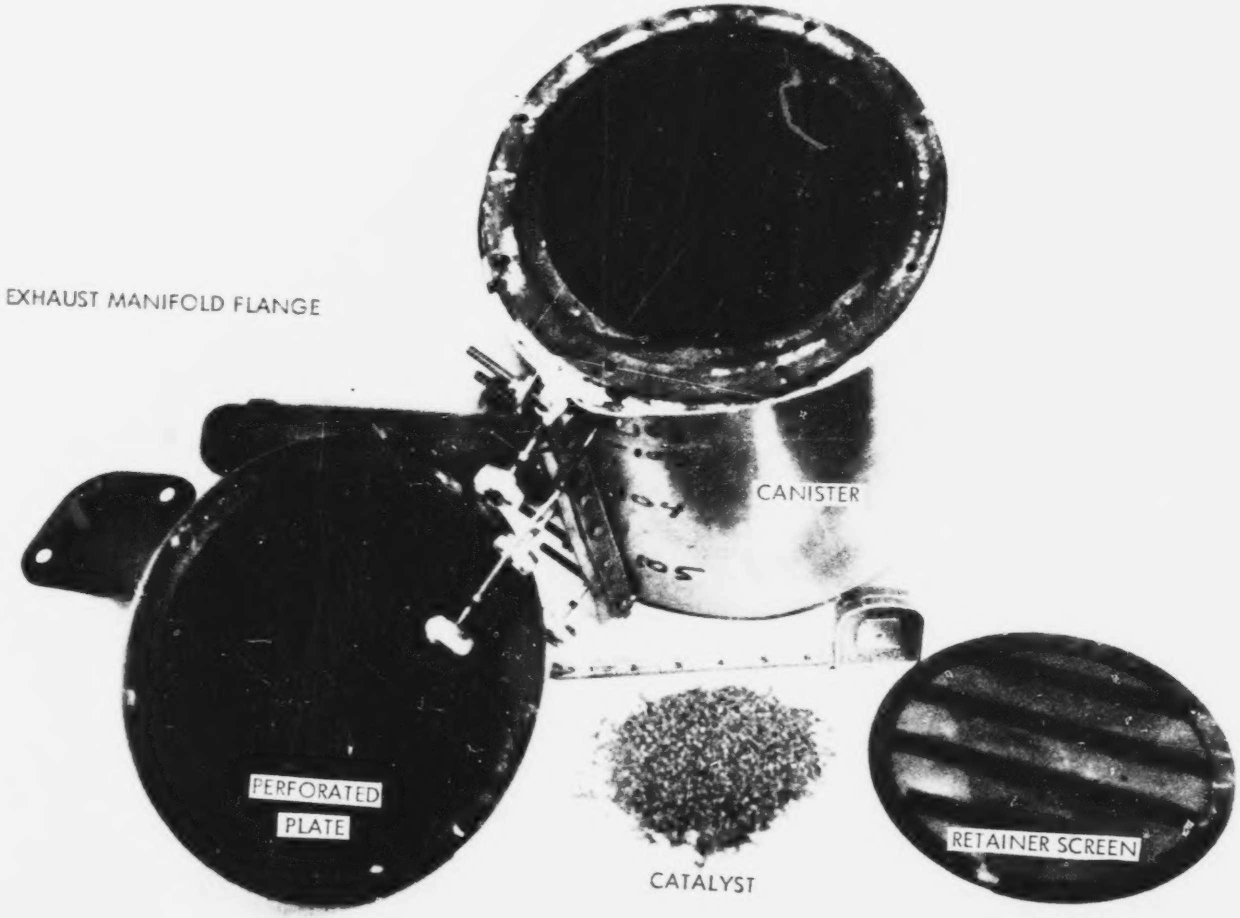

EXHAUST MANIFOLD FLANGE
CANISTER
PERFORATED PLATE
CATALYST
RETAINER SCREEN

FIGURE 8.8
FULL SCALE TRW-HARSHAW CATALYTIC CONVERTER

FIGURE 8.9
PERFORMANCE OF FULL SCALE TRW-HARSHAW CATALYTIC CONVERTER
23,000 V/V/Hr; 1230±30°F

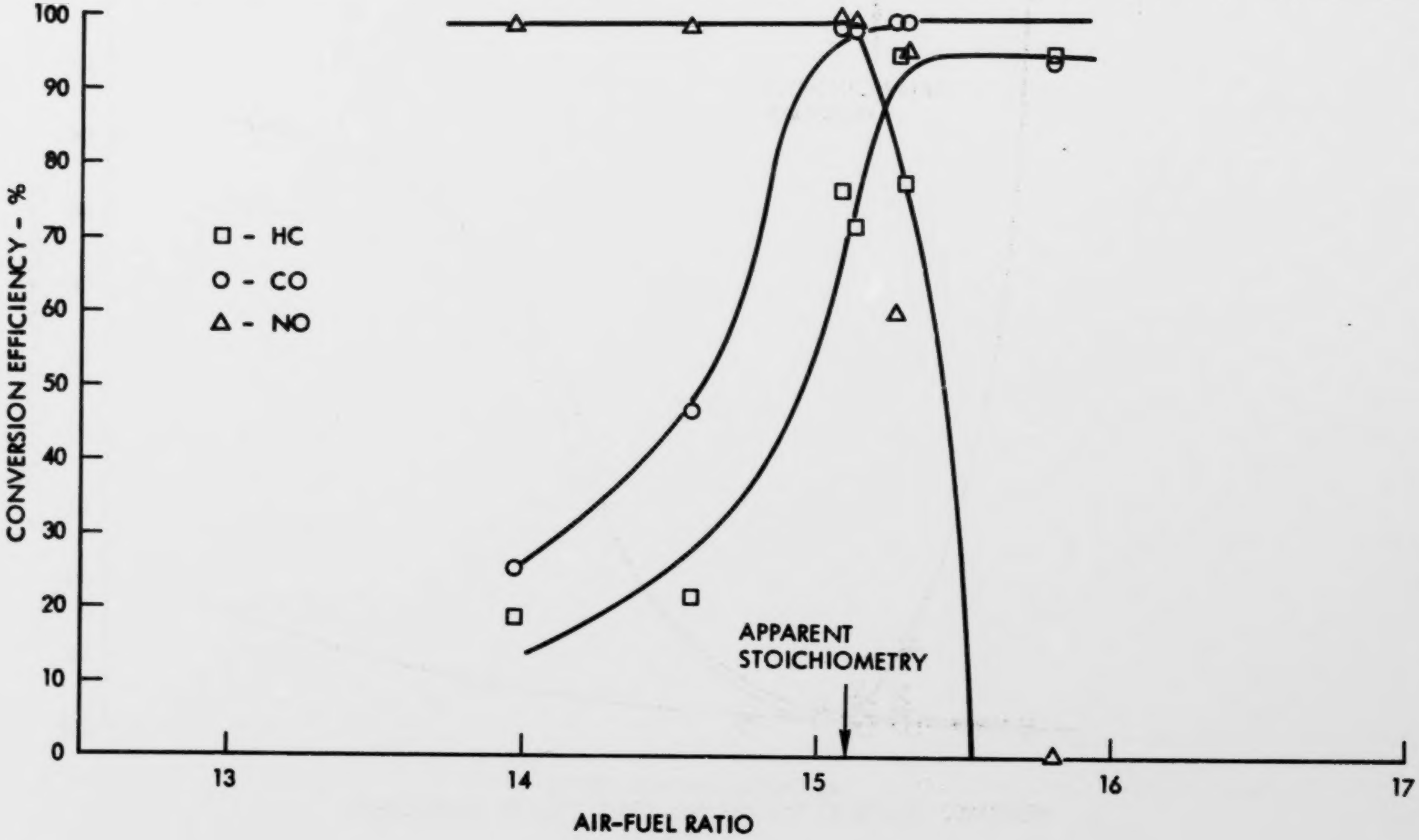
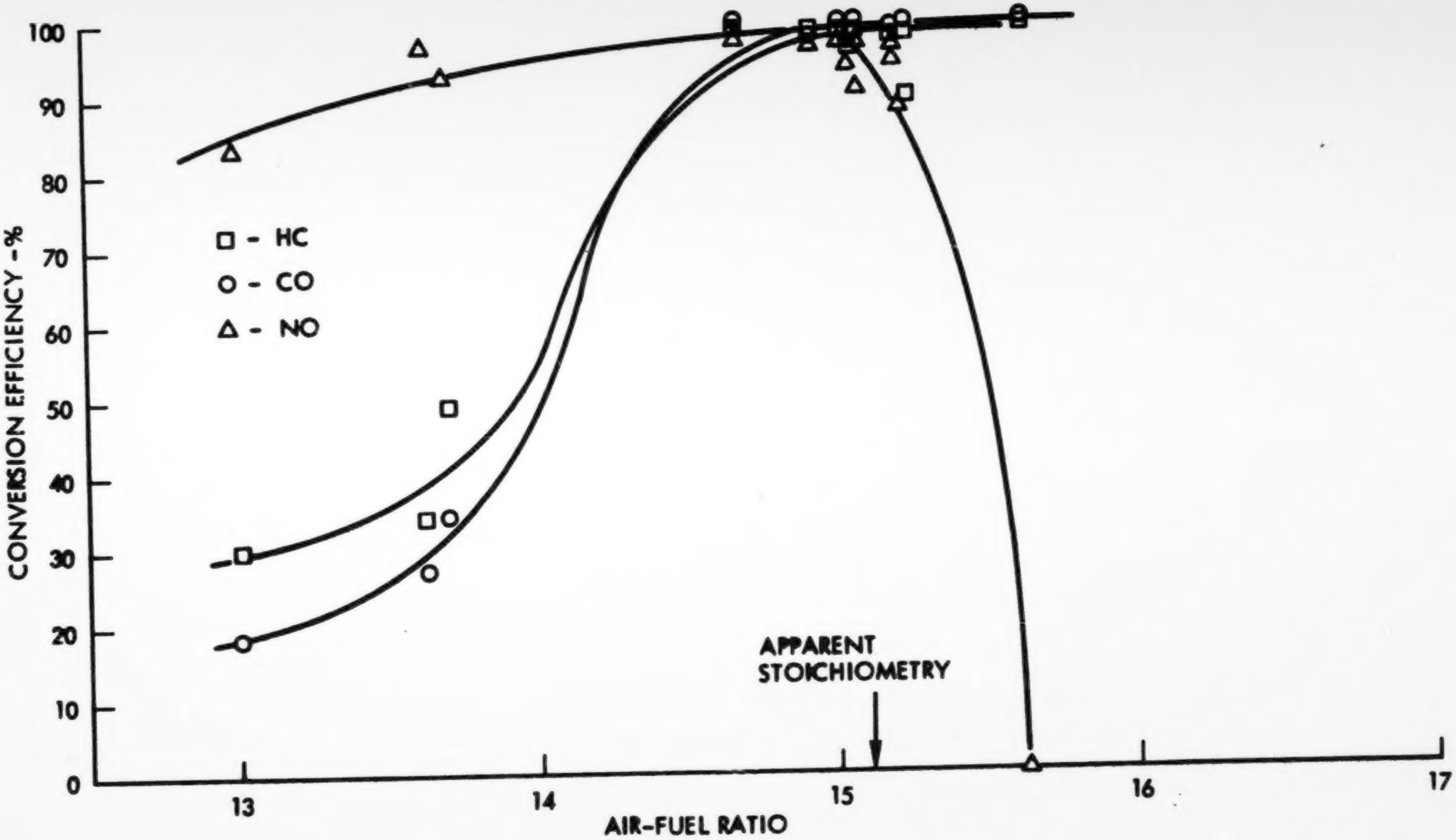


FIGURE 8.10
PERFORMANCE OF FULL SCALE TRW-HARSHAW CATALYTIC CONVERTER
40,000 V/V/Hr; 1520±20°F



Scaling up of the VW single cylinder converter by a factor of four did not alter the effectiveness of the TRW-Harshaw catalyst as a three-component catalyst; if anything, it proved more efficient. Comparison of Figures 8.2 and 8.9 and Figures 8.4, 8.5 and 8.10 reveals that the catalyst performance is almost identical even though the reductant and oxygen concentrations in the Vega exhaust are substantially higher than in the VW while the NO concentration is substantially lower. This tends to confirm the negligible effect of pollutant concentrations on conversions which was found in the bench scale tests. In comparing these data the difference in the apparent stoichiometric air-fuel ratios should be taken into account.

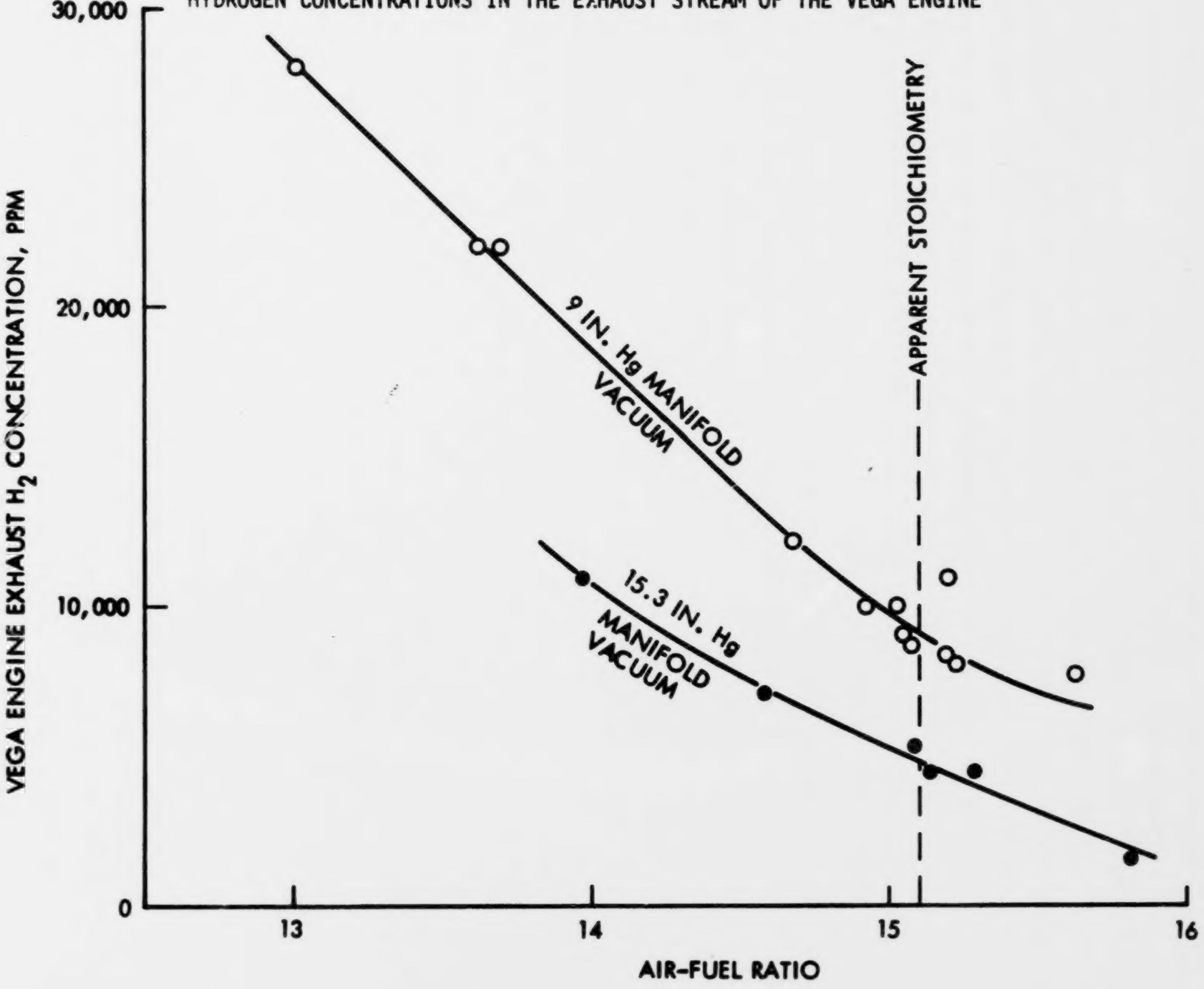
The only major difference between the sets of data taken from the two entirely different exhaust compositions is the CO conversion at the higher temperatures and richer-than stoichiometric mixtures. The Vega data indicates at least 20% higher CO conversion at equivalent A/F, even though the data was obtained at higher space velocities. The increased CO conversion extends the allowable variation in A/F on the rich side of stoichiometry by at least a factor of two beyond that of the VW exhaust data. Thus, according to the data in Figure 8.9, the allowable variation in A/F for a simultaneous total pollutant conversion of 80% is 7% (1.5% on the lean side of stoichiometry and 5.5% on the rich side). Without additional data it is impossible to offer a valid reason for the observed difference in CO conversion. It is within the realm of possibilities that the discrepancy is due to experimental error since a slight "off" point on either set of data can alter the shape of the curve substantially.

Hydrogen Measurements

Hydrogen concentrations in the steady state exhaust stream of the Vega were made using a Hewlett-Packard Laboratory Chromatograph. The chromatographic column of the device was calibrated using synthetic mixtures of exhaust gases containing N_2, C_3H_8, H_2, CO, CO_2 and O_2. The results of these tests are to be found in Figure 8.11.

The tests covered steady state operation at two manifold pressure levels at 1800 rpm and various air-fuel ratios.

FIGURE 8.11
HYDROGEN CONCENTRATIONS IN THE EXHAUST STREAM OF THE VEGA ENGINE



Ammonia Production

Under certain conditions ammonia, NH_3, can be formed within a catalytic converter by the reaction of NO and hydrogen. The latter's source can be gaseous or atomic hydrogen or hydrogen in the unoxidized hydrocarbons of the exhaust stream. Ammonia produced in the reducing bed of a dual bed catalyst system typically presents a problem in that NH_3 can be oxidized back to NO in the second, oxidizing bed. This reoxidation process cannot take place within a three-component catalytic system. However, while no standards have been set for vehicular ammonia emissions, it was desirable to make measurements to judge the magnitude of potential problems.

Experimental Procedures--The ammonia measurements were made using a wet chemical analysis technique modeled after that used by Segal, et al(4). A small stream of exhaust gas was drawn from the outlet of the TRW-Harshaw converter mounted on the Vega engine. The sample stream was bubbled through two NH_3 absorption baths set in series.

Each bath consisted of a flask containing 300 ml of a 2% by weight mixture of boric acid in water. The gas stream was admitted near the bottom of each flask through a glass frit and bubbled up through the acid to the flask outlet port. The flasks were chilled by submerging them in Dewar flasks filled with dry ice and water. The gas stream from the outlet of the second flask was pulled through a sample pump into a wet test meter which was used to measure the flow rate of the exhaust stream sample.

Sample gas was allowed to flow through the analysis stream for about 10 minutes at a rate of around 10 liters/minute. After NH_3 collection, Brom Cresol Green indicator was added to a sample from each flask and the samples were treated with a 0.04N solution of HCl to a yellow endpoint color. The analysis procedure and reference endpoint color were checked and calibrated using certified gas mixtures of 250 and 1000 ppm NH_3 in N_2.

The following equation was used to compute the concentration of NH_3 in the exhaust stream sample:

$$\text{ppm } NH_3 = \frac{(\text{cc's of HCl titrated})(0.04)(22{,}400)(\text{liters of sample/second})}{(60X \text{ minutes of sample collection})}$$

NH_3 Results--The concentration of ammonia in the exhaust of the catalytic converter are found in Figure 8.12. The two converter temperatures correspond to the manifold pressure levels indicated in Figure 8.9; the lower temperature is associated with the higher manifold vacuum. The dotted curves indicate the ratio of ammonia to total NO reduction as a function of air-to-fuel ratio.

Comparison of Figures 8.11 and 8.12 suggests that there is little dependence on the amount of engine-generated hydrogen and ammonia production in the catalyst. The higher rate of H_2 production in the engine at the higher manifold pressure does not correspond to higher NH_3 levels originating in the catalyst. Spot checks were made of the hydrogen conversion which showed that on the lean side of stoichiometry hydrogen conversion ranged between 80-100%, but conversion dropped sharply at mixture ratios below 15.0. These effects suggest that ammonia production depends on the amount of hydrogen, probably atomic, generated in the catalyst from the water-gas reaction, hydrocarbon decomposition or both.

There is a very strong dependence of ammonia generation on temperature and air-to-fuel ratios. At air-to-fuel ratios below 13.0 ammonia production approaches 100% of the total reduced NO; since the latter represents over 90% conversion of NO, practically all the NO generated in the engine is converted to ammonia. Fortunately, ammonia production in the catalyst is extremely low in the air-fuel ratio band and temperature level needed for successful three-component control.

Transient Tests - Data taken during engine cold starts substantially confirmed the "light off" measurements observed in the earlier bench scale tests. Figures 8.13 and 8.14 show the pollutant conversions and catalyst temperatures as a function of time after cold engine start.

Exact HC "light off" temperature determination could not be made as the catalyst bed tends to act as a hydrocarbon accumulator during the first minute of operation. Three minutes after the cold start the latter half of the converter is still below $1000^{o}F$ but all three pollutants are approaching their steady state values.

FIGURE 8.12
AMMONIA PRODUCTION OF THE TRW-HARSHAW THREE-COMPONENT CATALYST

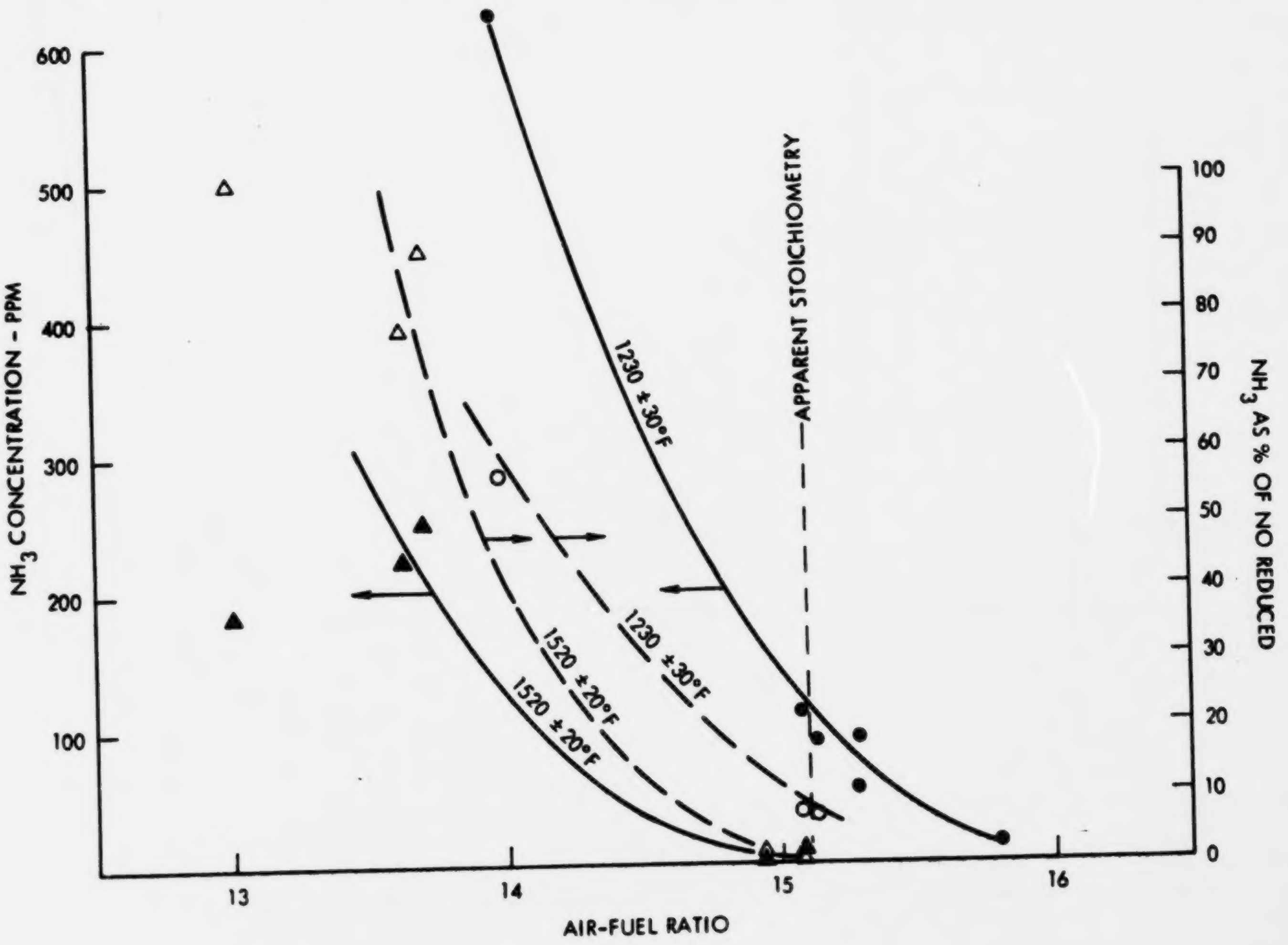


FIGURE 8.13
WARM-UP CONVERSION CHARACTERISTICS OF FULL SCALE CONVERTER

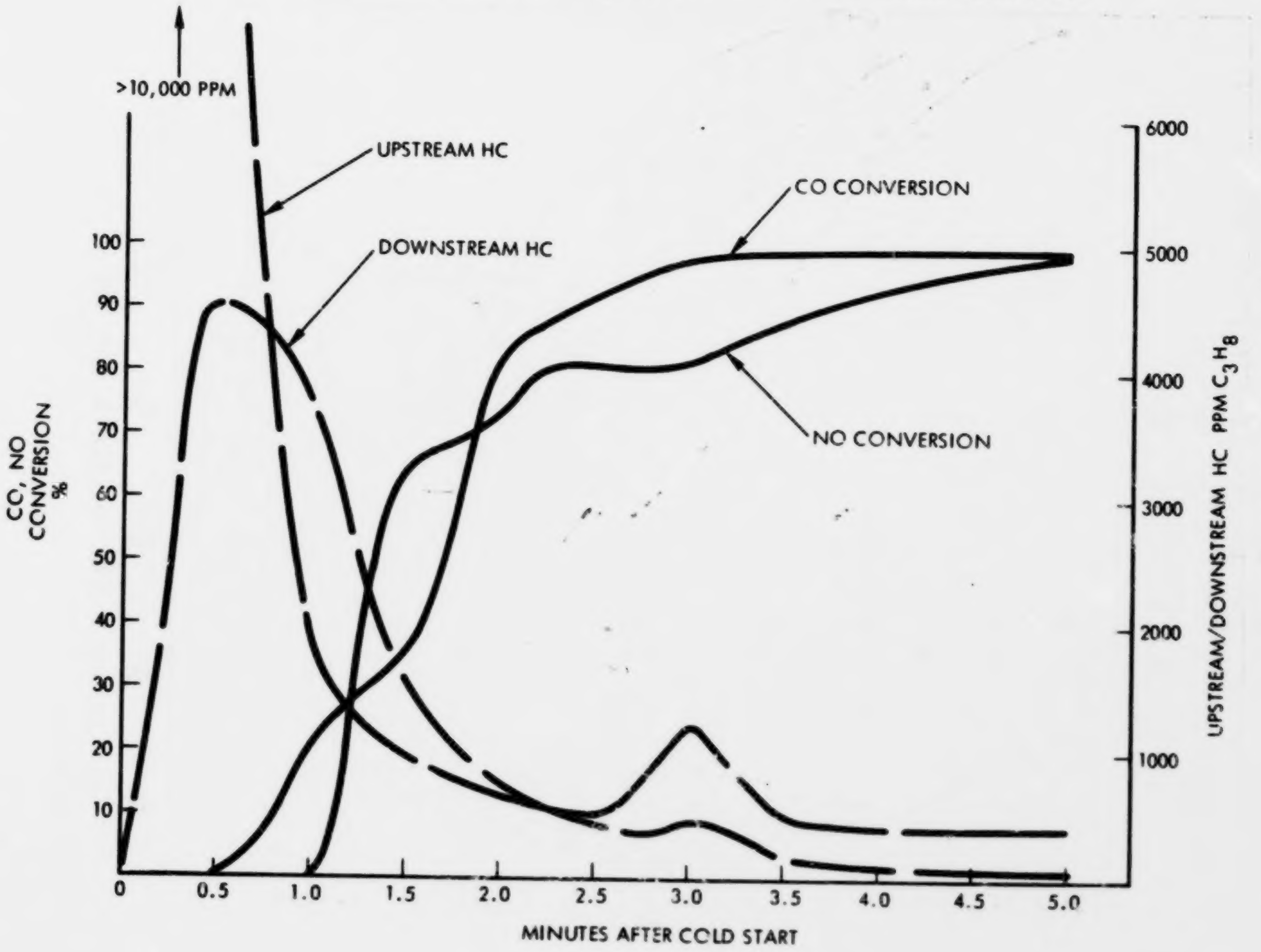
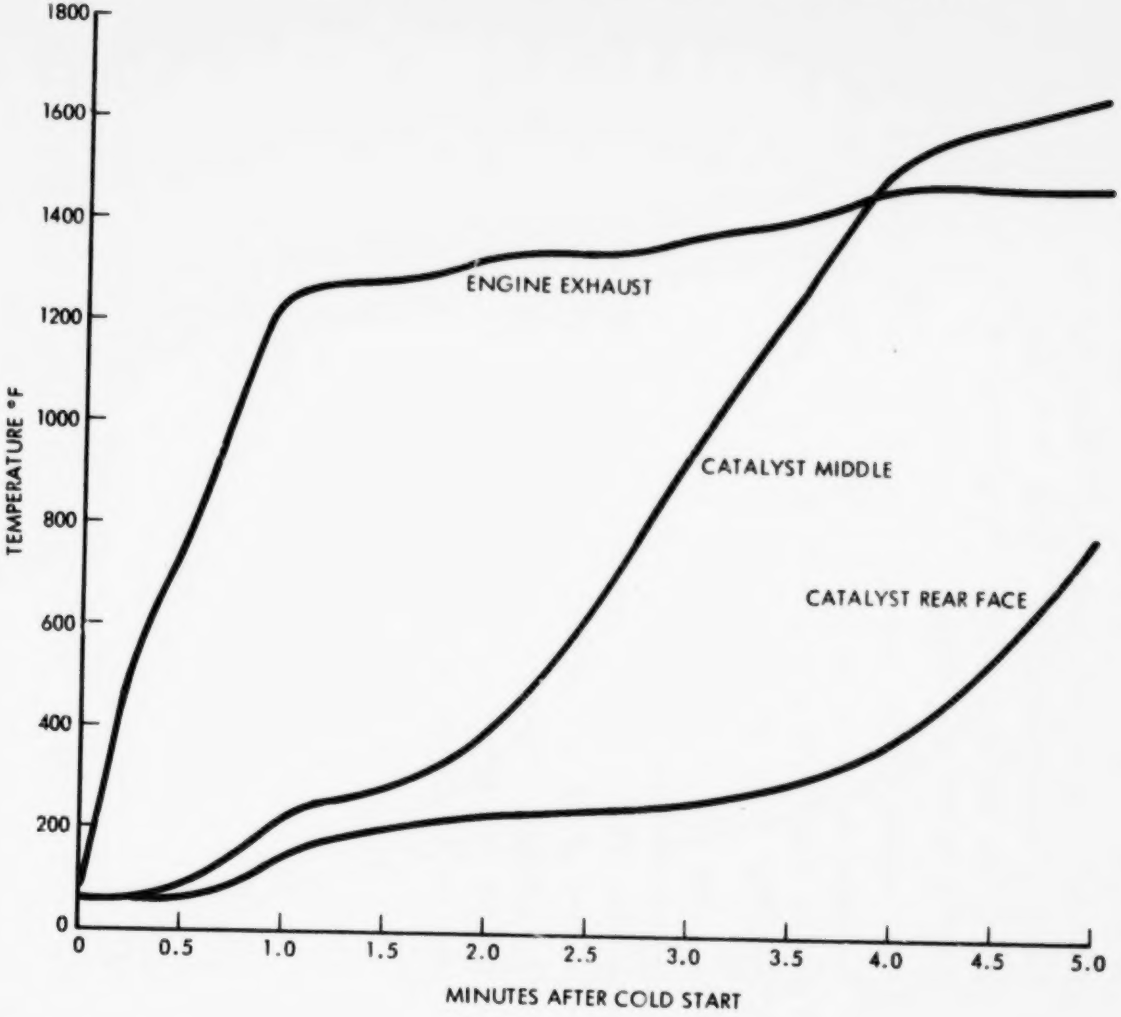


FIGURE 8.14
FULL SCALE CONVERTER THERMAL WARM-UP CHARACTERISTICS



Physical Changes - After about 50 hours of operation, the full scale converter was opened. A 10% volume reduction was noted and the bed had lost about 3% of its initial weight. The exposure time for the catalyst in the full scale converter was about one-half that of the single cylinder tests in which there was no apparent catalyst deterioration. Since the flow velocities in the full scale bed was the same or lower, it was concluded that much of the weight and volume loss was due to poor packing and vibration during Vega tests. While it is possible for the catalyst pellets to undergo sintering, visual checks of individual pellets did not uncover any geometry changes.

In order to test catalyst durability at relatively high temperatures, the catalyst bed was operated for more than one hour at the 1750°-1850°F range; the temperature was reduced and the catalyst activity was rechecked and found to be unaffected.

The catalyst appeared to be unaffected by whatever particulate matter the engine produced during the test time period. There was a small increase in the pressure drop across the bed with time, but that probably was due to the decreased bed volume rather than gross filling of flow passage with foreign materials. The maximum pressure drop across the bed was just below two inches of mercury at the highest observed space velocity (50,000 V/V/Hr at 1700°F).

9.0 CHARACTERISTICS OF UNIVERSAL OIL PRODUCTS CATALYTIC CONVERTER

9.1 Converter Description and Test Procedure

Two catalytic converters were supplied by Universal Oil Products of Des Plaines, Illinois for evaluation as hybrid vehicle emission control. The devices contained a proprietary catalyst which according to UOP contains less than $5 worth of platinum. The two devices differed only in size of the converter bed. The smaller converter was approximately 5 3/8 inches in diameter overall and had an apparent bed thickness of 2 1/4 inches. The larger converter was 6 1/2 inches in diameter overall and had an apparent bed thickness of 2 9/16 inches. Both converters had 2 inch diameter inlet and outlet tubes and conical inlet and outlet flow transition sections.

The converter inlet and outlet sections were slightly modified so they could be fastened to the machined outlet boss on the Vega exhaust manifold. The converters were placed as close as possible to the outlet; approximately 6 inches to the center of the converter bed. A photograph of the larger converter on the Vega engine can be seen in Figure 9.1.

The transient and steady state performance of the converters was examined on the Vega engine. The small size of the beds allowed the converters to come up to temperature quite rapidly. However, the light off of HC and CO was restricted due to the inability of the Vega mixture ratio to become lean rapidly enough.

9.2 Test Results

The steady state conversion performance of the converters is shown in Figures 9.2, 9.3 and 9.4. The devices acted as excellent oxidizing converters for lean mixture ratios. However, the NO reduction performance never exceeded more than 50% conversion for any condition of flow rate, temperature or air-fuel ratio.

A possible explanation for the low NO reduction is that the space velocity in the bed was too high. The estimated space velocity in the larger converter (nearly twice the bed volume as the smaller unit) was in excess of 200,000 V/V/Hr. at an engine flow rate of 40 SCFM or nearly seven times more than the TRW-Harshaw single cylinder canister or full scale catalytic converter.

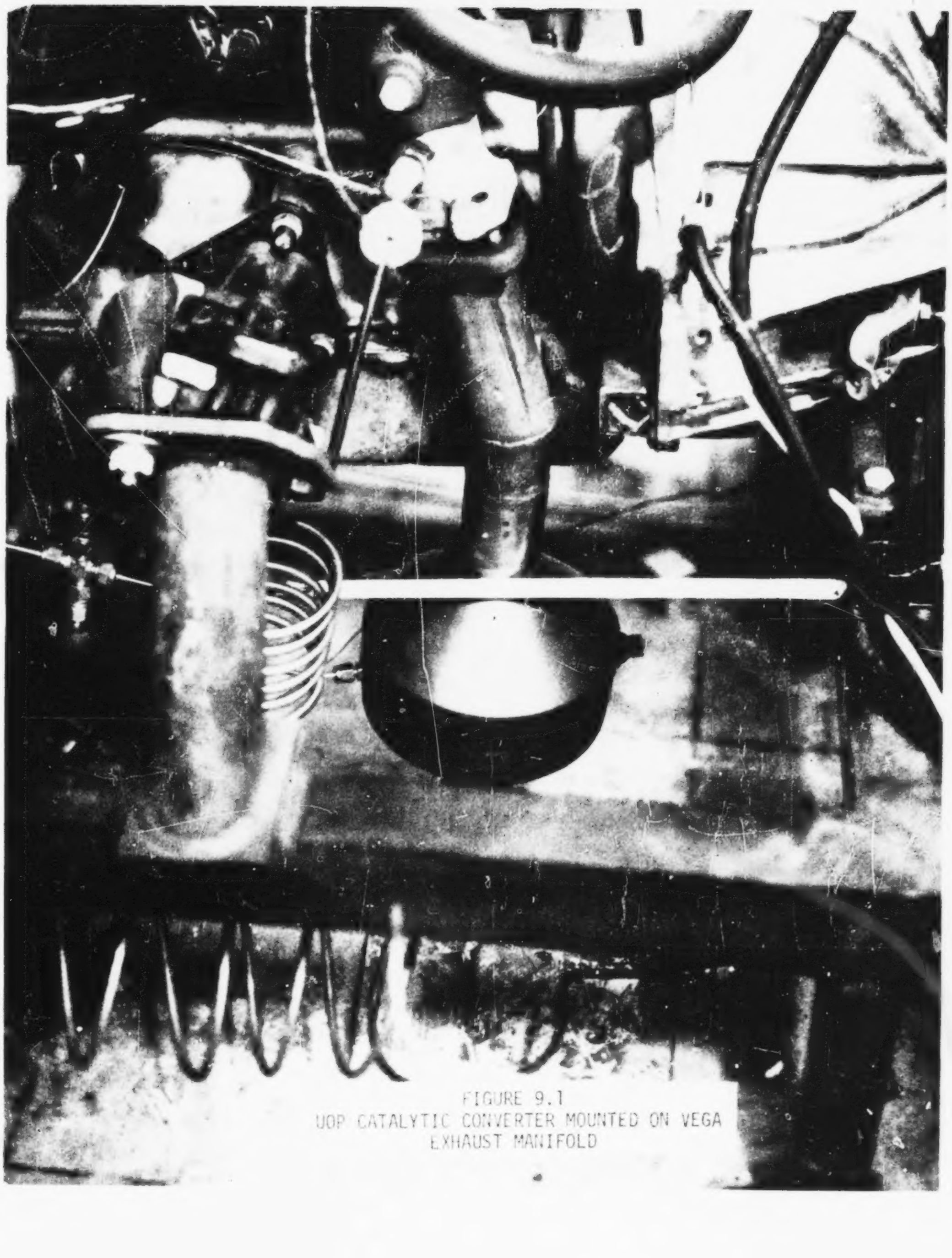


FIGURE 9.1
UOP CATALYTIC CONVERTER MOUNTED ON VEGA
EXHAUST MANIFOLD

FIGURE 9.2

UOP CATALYTIC CONVERTER PERFORMANCE ~38 SCFM, 1530± 50°F

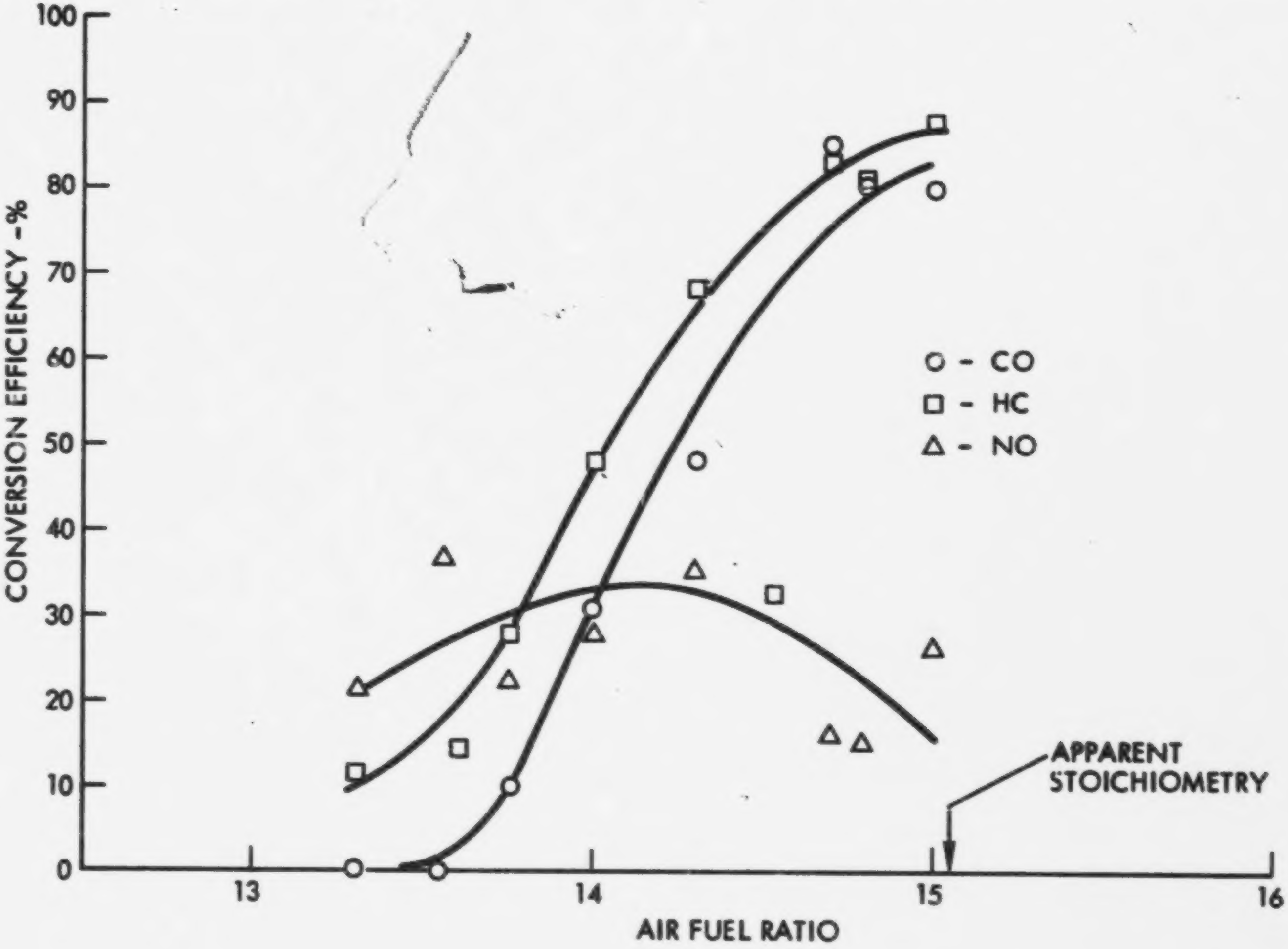


FIGURE 9.3

UOP CATALYTIC CONVERTER PERFORMANCE ~20 SCFM, 1340± 20°F

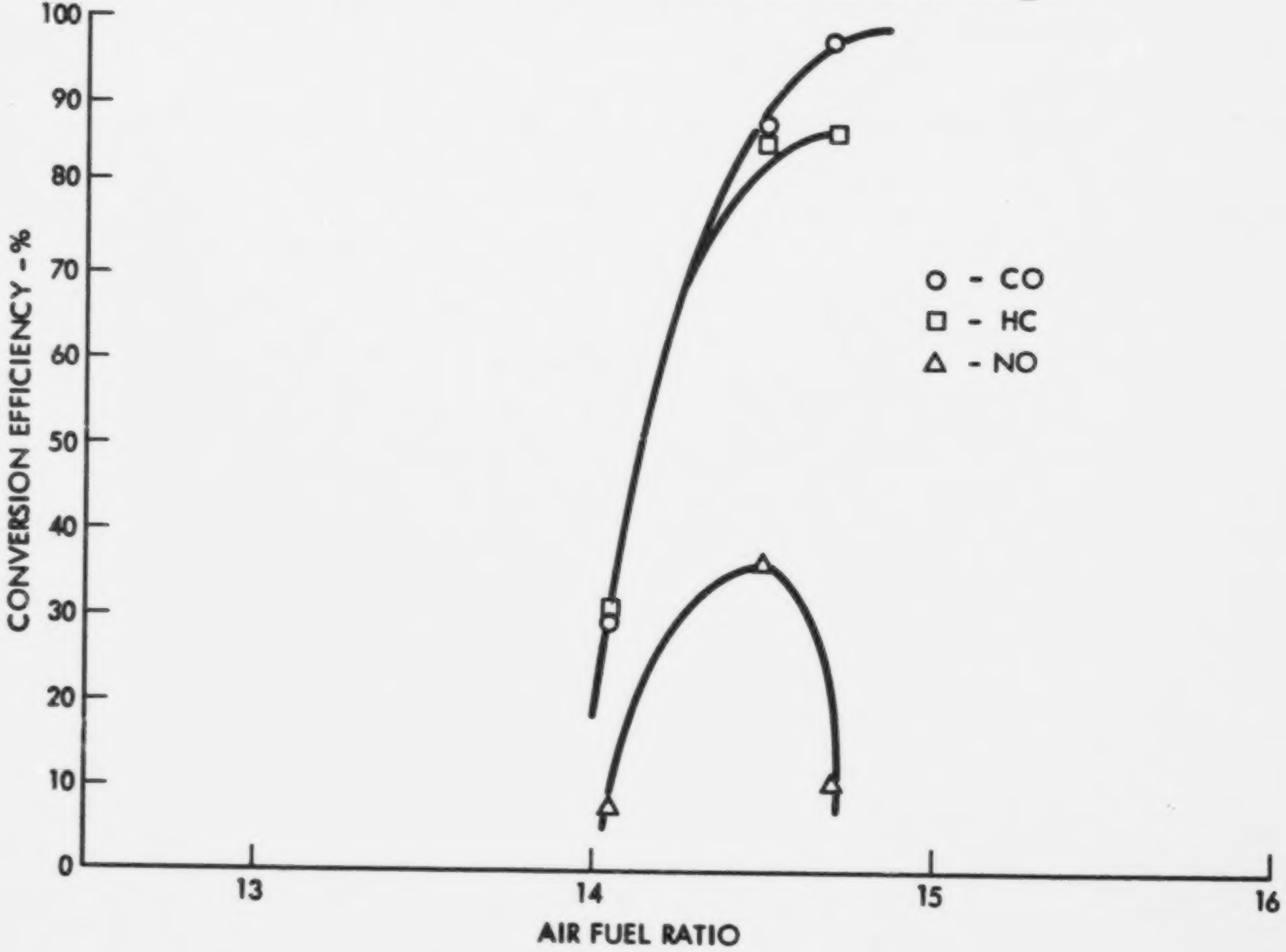
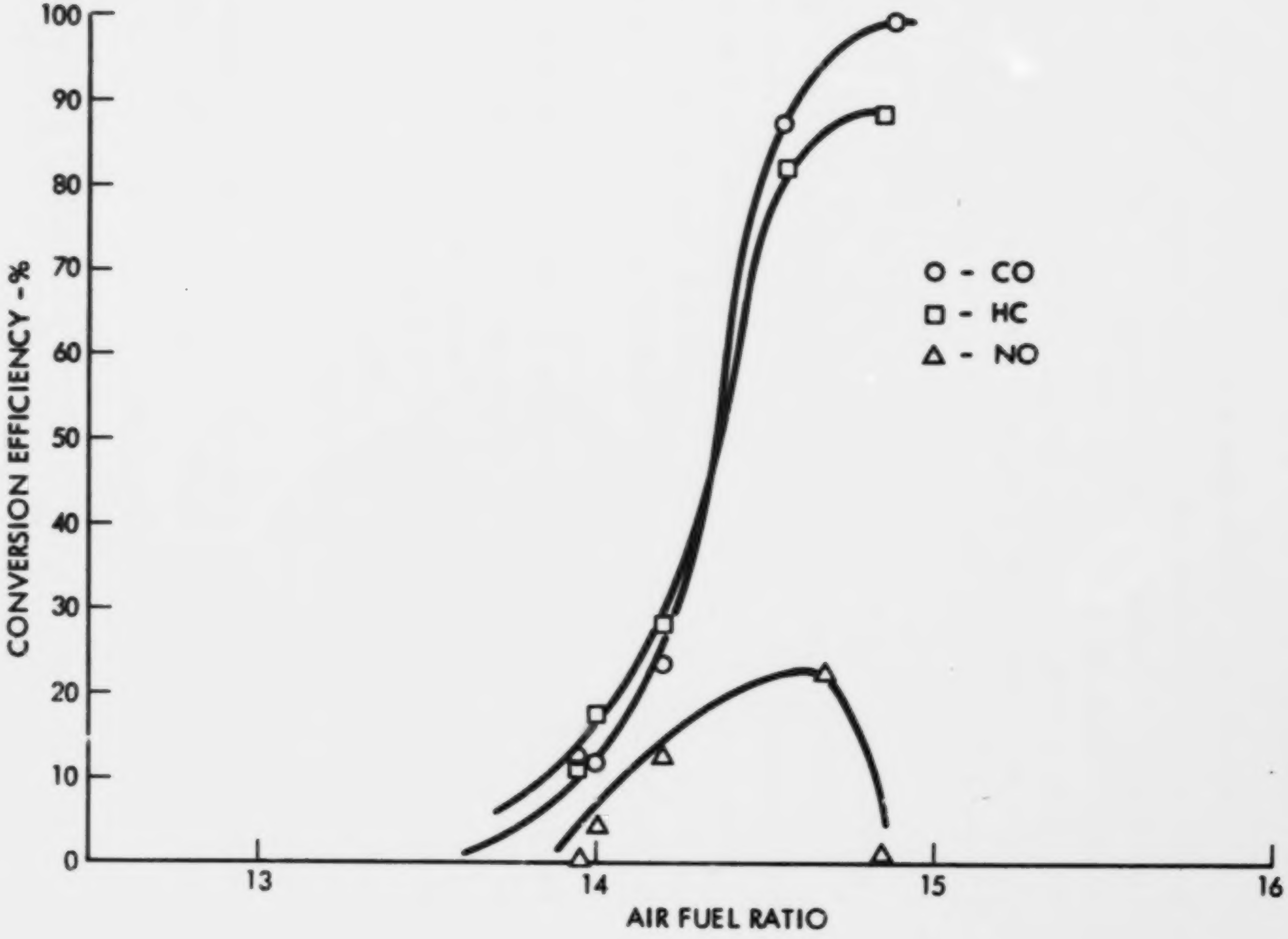


FIGURE 9.4

UOP CATALYTIC CONVERTER PERFORMANCE ~27 SCFM, 1365± 30°F



10.0 HYBRID SYSTEM FULL SCALE EMISSION TESTS

10.1 Introduction

A major goal of this program was to explore and demonstrate the ability of an ICE-battery hybrid system to meet the 1975-76 emission level standards. The advantages of hybrid operation were to be exploited--uncoupling of engine driveability from road demands during cold engine conditions, absence of rapid throttle changes, constant mixture ratio. Two control devices, a hydrocarbon accumulator and a three-component catalytic converter were to be used. This section describes the emission tests and test results.

10.2 Experimental Equipment

The full scale emission tests were conducted using the breadboard EMT equipment comprised of alternator, traction motor, power control units, batteries, gear box and dynamometer power absorber and flywheel inertial units. The engine used was the Chevrolet Vega engine modified as described in Appendix K; the catalytic converter was described in Section 8.3.2.

The double walled canister used in the hydrocarbon accumulator screening tests and the catalyst characterization tests was used as the full scale hydrocarbon accumulator canister. The canister was filled with a 6 inch deep layer of Pittsburgh Activated Carbon, BPL series. The accumulator was fed by a six foot long exhaust line from the outlet of the catalytic converter. The outlet of the accumulator fed into the inlet of a constant volume sampling system.

The major plumbing and instrumentation lines of the experimental equipment are indicated in Figure 10.1. Major elements of the system are:

- Laminar flow element flowmeter for measuring engine inlet flow rate.
- Fuel system composed of fuel pump, flowmeter, modified fuel injection system with manually controlled injection pulse duration.
- Engine with modified intake system and output shaft.
- Engine coupling to EMT power train.

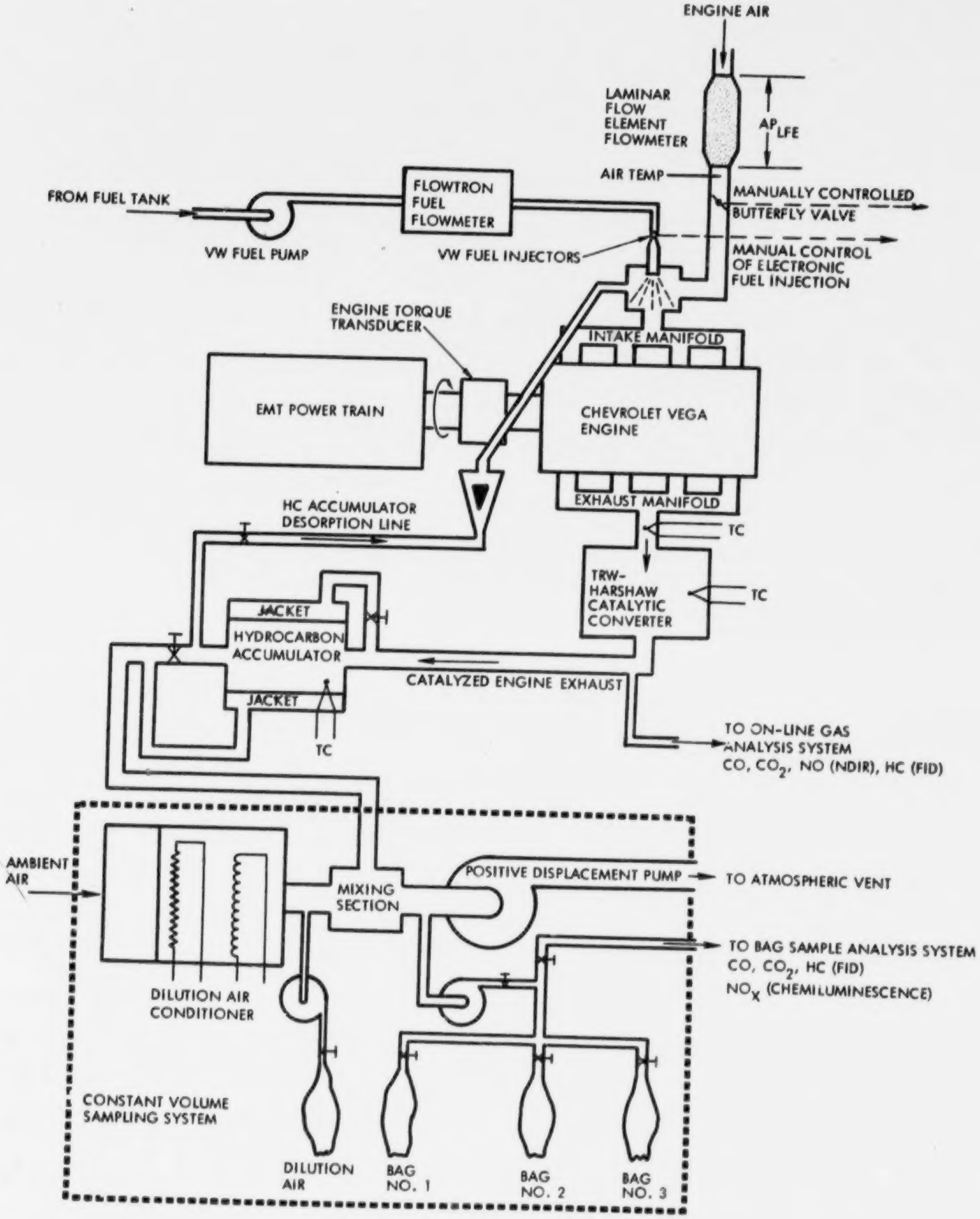

ENGINE AIR
LAMINAR FLOW ELEMENT FLOWMETER
ΔP_{LFE}
AIR TEMP
MANUALLY CONTROLLED BUTTERFLY VALVE
FROM FUEL TANK
VW FUEL PUMP
FLOWTRON FUEL FLOWMETER
VW FUEL INJECTORS
MANUAL CONTROL OF ELECTRONIC FUEL INJECTION
ENGINE TORQUE TRANSDUCER
INTAKE MANIFOLD
EMT POWER TRAIN
CHEVROLET VEGA ENGINE
EXHAUST MANIFOLD
TC
HC ACCUMULATOR DESORPTION LINE
TRW-HARSHAW CATALYTIC CONVERTER
TC
JACKET
HYDROCARBON ACCUMULATOR
JACKET
CATALYZED ENGINE EXHAUST
TC
TO ON-LINE GAS ANALYSIS SYSTEM
CO, CO_2, NO (NDIR), HC (FID)
AMBIENT AIR
MIXING SECTION
POSITIVE DISPLACEMENT PUMP
TO ATMOSPHERIC VENT
TO BAG SAMPLE ANALYSIS SYSTEM
CO, CO_2, HC (FID)
NO_X (CHEMILUMINESCENCE)
DILUTION AIR CONDITIONER
CONSTANT VOLUME SAMPLING SYSTEM
DILUTION AIR
BAG NO. 1
BAG NO. 2
BAG NO. 3

FIGURE 10.1
MAJOR HARDWARE COMPONENTS OF FULL SCALE EMISSION TESTS

- TRW-Harshaw catalytic converter instrumented to provide temperature and pressure drop information as well as a continuous sample of converter outlet gas composition (CO, CO_2, NO, HC, O_2).
- Hydrocarbon accumulator with bypass lines for continued heating of the accumulator bed after engine cold start and a desorption line in series with a rotameter through which the desorbed hydrocarbons flowed back to intake manifold of the engine.
- Beckman constant volume sampling (CVS) system composed of dilution air conditioning system, mixing section, positive displacement pump, sample pumps and bags.

10.3 Experimental Procedure for Performing Emission Tests

The breadboard EMT equipment was shown in the previous contractual work to have serious component inefficiencies which would require the average engine power level to be raised above those which would be required in the more advanced and efficient systems studied in the analytic portion of this report. Therefore, it was necessary to perform emission tests as if the advanced hardware were actually in place and run the internal combustion engine at a power level which the analyses of Section 5 indicated would be required.

The following operating procedures were adopted in running the emission tests according to the Federal Register of July 1971:

- The Vega engine and EMT systems were cold soaked in the laboratory for a period in excess of 15 hours. Test cell temperatures ran from 55°F to 65°F during the cold soak time.
- Prior to run start--
  - all flow transducers were zeroed
  - all gas analysis equipment was zeroed and spanned with certified span gases
  - throttle was opened to give approximately 9" Hg vacuum manifold at 1800 rpm
  - electronic choke of the fuel injection system was set to maximum, giving a starting mixture air-fuel ratio estimated around 8:1 to 10:1
  - the fuel pump and recorders were started
  - the CVS system and sample pump started filling the "transient bag."
- Immediately after the CVS sample pump was turned on the engine starter motor was engaged.

- As soon as the engine started it accelerated up in speed until the EMT system began loading it and controlled its speed at 1800 rpm.
- The choke was relieved while the throttle was slightly changed to give between 9 and 10" Hg vacuum at 1800 rpm. The choke was removed as rapid as possible, consistent with maintaining engine speed and electrical output from the EMT system alternator. Generally, the choke was fully off within two minutes after cranking.
- At approximately 215 seconds after engine start, the engine was throttled up to about 5" Hg vacuum, corresponding to about 26 shaft horsepower at 1800 rpm. The time of throttle change was based on the sum of 15 seconds allowed from engine start to placing the car's transmission in gear (according to the Federal test procedure), plus 200 seconds to the time the car would have reached 42 mph on the Federal driving cycle. At that time it was assumed that the hybrid would begin operating in the highway mode and the engine would throttle up to a power level equal to road load at 55 mph, or about 26 hp accounting for expected system inefficiencies.
- At 323 seconds (15+308) the throttle was returned to 9 or 10" Hg for the remainder of the transient bag and the full duration of the second or "stabilized" bag.
- The starting procedure for the hot start bag was identical except that the choke was only slightly or not used at all. Throttling up at 215 seconds and throttling down at 323 seconds was as during the cold start transient bag.
- In all other respects, the emission tests followed the procedure outlined in the July 2, 1971 Federal Register.

10.4 Full Scale System Emission Results

The results for several of the cold start tests spanning a two-week period are shown in Table 10.1. The data is presented in chronological order to indicate a measure of the learning process we experienced. The data shows the actual grams of HC, CO and NO_x for the three bags of the Federal test procedure. The fourth column shows the emission results in grams per mile after the appropriate test procedure weighting factors are applied to the three bag results. The final column presents some remarks about each test.

The emission control system was very effective in terms of hydrocarbon and oxides of nitrogen control. The combined use of the hydrocarbon accumulator and three-component catalyst resulted in hydrocarbon emissions ranging from a low of 34% to a high of 73% of the 1975 standards. The hydrocarbon accumulator was a vital factor for the meeting of the standards. In the test of 1/4/72 the accumulator was bypassed and the total HC emissions were 2.8 times above the standards, even though the hot start and stabilized bag hydrocarbons did not differ greatly from the othe runs.

The NO_x results ranged from a low of 15% to a high of 80% of the 1976 standards. The lower values were associated with the earlier tests where the choke control during the cold start was more erratic and the engine exhaust NO did not come up as rapidly as it did in later tests. The most troublesome pollutant was CO. The CO standard was met with a 70% margin on one occasion; the standard was slightly exceeded during another test. Examination of the bag data shows the cold start CO to be the major factor in the total CO emissions.

There is considerable reason to believe that the modification of the Vega's air-fuel control was partially responsible for the relative poor CO control. As previously reported, the modified Vega generally required two minutes for complete choke removal. The fuel injectors were situated such that the spray of the injectors impinged directly on the floor of the intake manifold. It is probable that fuel puddling occurred on the cold manifold walls and thus the engine required an excessively rich mixture during start-up. Venturi action and turbulence of a standard carburetor might have provided sufficient fuel-air mixing to reduce the starting enrichment requirements. Previous experience(1) with the VW 1600 showed that intake port injection allowed the choke to be removed within 30 seconds after engine start. It is probable that a properly designed carburetor system employing a quick choke, standard carburetor or direct intake port injection could dramatically reduce cold start CO levels.

TABLE 10.1

FULL SCALE HYBRID SYSTEM EMISSION TEST RESULTS

Test Date	Cold Start Bag, grams			Hot Start Bag, grams			Stabilized Bag, grams			Emissions, gms/mi			Remarks
	HC	CO	NO_x*	HC	CO	NO_x*	HC	CO	NO_x*	HC	CO	NO_x*	
12/22/71	1.63	55.3	0.52	0.24	1.08	0.16	0.77	14.7	0.12	0.21	5.22	0.06	poor hot start excessive enrichment
12/27/71	1.25	55.3	0.87	0.25	2.20	0.54	0.38	4.3	0.21	0.14	3.92	0.12	
12/28/71	1.72	59.5	0.28	1.27	22.1	0.54	0.41	4.41	0.33	0.25	5.65	0.10	too slow choke relief
12/30/71	1.68	41.9	3.22	0.40	6.60	.21	0.38	4.3	0.32	0.18	3.47	0.24	
1/3/72	2.56	49.6	3.88	0.40	2.66	0.44	0.90	9.54	0.43	0.30	4.33	0.31	very poor hot start
1/4/72	17.5	45.2	0.66	0.21	2.43	2.66	0.95	6.95	0.50	1.15	3.69	0.31	no hydrocarbon accumulator
1/6/72	2.84	46.8	3.48	0.84	1.63	0.56	0.50	2.64	0.58	0.29	3.20	0.32	no detectable NH_3

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*NO_x as NO_2

APPENDIX A

AIR POLLUTION CONTROL OFFICE

ADVANCED AUTOMOTIVE POWER SYSTEMS PROGRAM

"Vehicle Design Goals - Six Passenger Automobile"

(Revision B - February 11, 1971 - 11 Pages)

The design goals presented below are intended to provide:

A common objective for prospective contractors.

Criteria for evaluating proposals and selecting a contractor.

Criteria for evaluating competitive power systems for entering first generation system hardware.

The derived criteria are based on typical characteristics of the class of passenger automobiles with the largest market volume produced in the U.S. during the model years 1969 and 1970. It is noted that emissions, volume and most weight characteristics presented are maximum values while the performance characteristics are intended as minimum values. Contractors and prospective contractors who take exceptions must justify these exceptions and relate these exceptions to the technical goals presented herein.

1. Vehicle weight without propulsion system - W_o.

W_o is the weight of the vehicle without the propulsion system and includes, but is not limited to: body, frame, glass and trim, suspension, service brakes, seats, upholstery, sound absorbing materials, insulation, wheels (rims and tires), accessory ducting, dashboard instruments and accessory wiring, passenger compartment heating and cooling devices and all other components not included in the propulsion system. It also includes the air conditioner compressor, the power steering pump and the power brakes actuating device.

W_o is fixed at 2700 lbs.

2. Propulsion system weight - W_p.

W_p includes the energy storage unit (including fuel and containment), power converter (including both functional components and controls) and power transmitting components to the driven wheels. It also includes the exhaust system, pumps, motors, fans and fluids necessary for operation of the propulsion system and any propulsion system heating or cooling devices.

The maximum allowable propulsion system weight, W_{pm}, is 1600 lbs. However, light weight propulsion systems are highly desired. (Equivalent 1970 propulsion system weight with a spark ignition engine is 1300 lbs.)

3. Vehicle curb weight - W_c

$W_c = W_o + W_p$

The maximum allowable vehicle curb weight, W_{cm}, is 4300 lbs. (2700 + 1600 max. = 4300)

4. Vehicle test weight - W_t

$W_t = W_c + 300$ lbs. W_t is the vehicle weight at which all accelerative maneuvers, fuel economy and emissions are to be calculated. (Items 8c, 8d, 8e)

The maximum allowable test weight, W_{tm}, is 4600 lbs. (2700 + 1600 max. + 300 = 4600)

5. Gross vehicle weight - W_g

$W_g = W_c + 1000$ lbs. W_g is the gross vehicle weight at which sustained cruise grade velocity capability is to be calculated. (Item 8f) The 1000 lbs. load simulates a full load of passengers and baggage.

The maximum allowable gross vehicle weight, W_{gm}, is 5300 lbs. (2700 + 1600 max. + 1000 = 5300)

6. Propulsion system volume - V_p

V_p includes all items identified under item 2. V_p shall be packagable in such a way that the volume encroachment on either the passenger or luggage compartment is not significantly different than today's (1970) standard full size family car. Necessary external appearance (styling) changes will be minor in nature. V_p shall also be packagable in such a way that the handling characteristics of the vehicle do not depart significantly from a 1970 full size family car.

The maximum allowable volume assignable to the propulsion system, V_{pm}, is 35 ft^3.

7. Emission Goals

The vehicle when tested for emissions in accordance with the procedure outlined in the November 10, 1970 Federal Register shall have a weight of W_t. The emission goals for the vehicle are:

Hydrocarbons*	- 0.14 grams/mile maximum
Carbon Monoxide	- 4.7 grams/mile maximum
Oxides of Nitrogen**	- 0.4 grams/mile maximum
Particulates	- 0.03 grams/mile maximum

*Total hydrocarbons (using 1972 measurement procedures) plus total oxygenates. Total oxygenates including aledhydes will not be more than 10 percent by weight of the hydrocarbons or 0.014 grams/mile, whichever is greater.

**measured or computed as NO_2.

8. Start-up, Acceleration, and Grade Velocity Performance.

a. Start-up:

The vehicle must be capable of being tested in accordance with the procedure outlined in the November 10, 1970 Federal Register without special start-up/warm-up procedures.

The maximum time from key on to reach 65 percent full power is 45 sec. Ambient conditions are 14.7 psia pressure, 60°F temperature.

Powerplant starting techniques in low ambient temperatures shall be equivalent to or better than the typical automobile spark-ignition engine. Conventional spark-ignition engines are deemed satisfactory if after a 24-hour soak at -20°F the engine achieves a self-sustaining idle condition without further driver input within 25 seconds. No starting aids external to the normal vehicle system shall be needed for -20°F starts or higher temperatures.

b. Idle operation conditions:

The fuel consumption rate at idle operating condition will not exceed 14 percent of the fuel consumption rate at the maximum design power condition. Recharging of energy storage systems is exempted from this requirement. Air conditioning is off, the power steering pump and power brake actuating device, if directly engine driven, are being driven but are unloaded.

The torque at transmission output during idle operation (idle creep torque) shall not exceed 40 foot-pounds, assuming conventional rear axle ratios and tire sizes. This idle creep torque should result in level road operation in high gear which does not exceed 18 mph.

c. Acceleration from a standing start:

The minimum distance to be covered in 10.0 sec. is 440 ft. The maximum time to reach a velocity of 60 mph is 13.5 sec. Ambient conditions are 14.7 psia, 85°F. Vehicle weight is W_t. Acceleration is on a level grade and initiated with the engine at the normal idle condition.

d. Acceleration in merging traffic:

The maximum time to accelerate from a constant velocity of 25 mph to a velocity of 70 mph is 15.0 sec. Time starts when the throttle is depressed. Ambient conditions are 14.7 psia, 85°F. Vehicle weight is W_t, and acceleration is on level grade.

e. Acceleration, DOT High Speed Pass Maneuver:

The maximum time and maximum distance to go from an initial velocity of 50 mph with the front of the automobile (18 foot length assumed) 100 feet behind the back of a 55 foot truck traveling at a constant 50 mph to a position where the back of the automobile is 100 feet in front of the 55 foot truck is, 15 sec. and 1400 ft. The entire maneuver takes place in a traffic lane adjacent to the lane in which the truck is operated. Vehicle will be accelerated until the maneuver is completed or until a maximum speed of 80 mph is attained, whichever occurs first. Vehicle acceleration ceases when a speed of 80 mph is attained, the maneuver then being completed at a constant 80 mph. (This does not imply a design requirement limiting the maximum vehicle speed to 80 mph.) Time starts when the throttle is depressed. Ambient conditions are 14.7 psia, 85°F. Vehicle weight is W_t, and acceleration is on level grade.

f. Grade velocity:

The vehicle must be capable of starting from rest on a 30 percent grade and accelerating to 15 mph and sustaining it. This is the steepest grade on which the vehicle is required to operate in either the forward or reverse direction.

The minimum cruise velocity that can be continuously maintained on a 5 percent grade with an accessory load of 4 hp shall be not less than 60 mph.

The vehicle must be capable of achieving a velocity of 65 mph up a 5 percent grade and maintaining this velocity for a period of 180 seconds when preceded and followed by continuous operation at 60 mph on the same grade (as above).

The vehicle must be capable of achieving a velocity of 70 mph up a 5 percent grade and maintaining this velocity for a period of 100 seconds when preceded and followed by continuous operation at 60 mph on the same grade (as above).

The minimum cruise velocity that can be continuously maintained on a level road (zero grade) with an accessory load of 4 hp shall be not less than 85 mph with a vehicle weight of W_t.

Ambient conditions for all grade specifications are 14.7 psia 85°F. Vehicle weight is W_g for all grade specifications except the zero grade specification.

The vehicle must be capable of providing performance (Paragraphs 8c, 8d, 8e, 8f) within 5 percent of the stated 85°F values, when operated at ambient temperatures from -20°F to 105°F.

9. Minimum vehicle range:

Minimum vehicle range without supplementing the energy storage will be 200 miles. The minimum range shall be calculated for, and applied to each of the two following modes: 1) A city-suburban mode, and 2) a cruise mode.

Mode 1: Is the driving cycle which appears in the November 10, 1970 Federal Register. For vehicles whose performance does not depend on the state of energy storage, the range may be calculated for one cycle and ratioed to 200 miles. For vehicles whose performance does depend on the state of energy storage the Federal driving cycle must be repeated until 200 miles have been completed.

Mode 2: Is a constant 70 mph cruise on a level road for 200 miles.

The vehicle weight for both modes shall be, initially, W_t. The ambient conditions shall be a pressure of 14.7 psia and temperatures of 60°F, 85°F and 105°F. The vehicle minimum range shall not decrease by more than 5 percent at an ambient temperature of -20°F.

For hybrid vehicles, the energy level in the power augmenting device at the completion of operation will be equivalent to the energy level at the beginning of operation.

10. System thermal efficiency:

System thermal efficiency will be calculated by two methods:

A. A "fuel economy" figure based on 1) miles per gallon (fuel type being specified) and 2) the number of Btu per mile required to drive the vehicle over the 1972 Federal driving cycle which appears in the November 10, 1970 Federal Register. Fuel economy is based on the fuel or other forms of energy delivered at the vehicle. Vehicle weight is W_t.

B. A "fuel economy" figure based on 1) miles per gallon (fuel type being specified) and 2) the number of Btu per mile required to drive the vehicle at constant speed, in still air, on level road, at speeds of 20, 30, 40, 50, 60, 70 and 80 mph. Fuel economy is based on the fuel or other forms of energy delivered at the vehicle. Vehicle weight is W_t.

In both cases, the system thermal efficiency shall be calculated with sufficient electrical, power steering and power brake loads in service to permit safe operation of the automobile. Calculations shall be made with and without air conditioning operating. The ambient conditions are 14.7 psia and temperatures of 60°F, 85°F and 105°F. Calculations shall be made with heater operating at ambient conditions of 14.7 psia and 30°F (18,000 Btu/hr.).

11. Air drag calculation:

    The product of the drag coefficient, C_d, and the frontal area, A_f, is to be used in air drag calculations. The product C_dA_f has a value of 12 ft^2. The air density used in computations shall correspond to the applicable ambient air temperature.

12. Rolling resistance:

    Rolling resistance, R, is expressed in the equation $R = W/65 [1 + (1.4 \times 10^{-3}V) + (1.2\ 10^{-5}V^2)]$ lbs. V is the vehicle velocity in ft/sec. W is the vehicle weight in lbs.

13. Accessory power requirements:

    The accessories are defined as subsystems for driver assistance and passenger convenience, not essential to sustaining the engine operation and include: the air conditioning compressor, the power steering pump, the alternator (except where required to sustain operation), and the power brakes actuating device. The accessories also include a device for heating the passenger compartment if the heating demand is not supplied by waste heat.

    Auxiliaries are defined as those subsystems necessary for the sustained operation of the engine and include condensor fan(s), combustor fan(s), fuel pumps, lube pumps, cooling fluid pumps, working fluid pumps and the alternator when necessary for driving electric motor driven fans or pumps.

    The maximum intermittent accessory load, P_{aim}, is 10 hp (plus the heating load, if applicable). The maximum continuous accessory load, P_{acm}, is 7.5 hp (plus the heating load if applicable). The average accessory load, P_{aa}, is 4 hp.

    If accessories are driven at variable speeds, the above values apply. If the accessories are driven at constant speed, P_{aim} and P_{acm} will be reduced by 3 hp.

14. Passenger comfort requirements:

    Heating and air conditioning of the passenger compartment shall be at a rate equivalent to that provided in the present (1970) standard full size family car.

Present practice for maximum passenger compartment heating rate is approximately 30,000 Btu/hr. For an air conditioning system at 110°F ambient, 80°F and 40% relative humidity air to the evaporator, the rate is approximately 13,000 Btu/hr.

15. Propulsion system operating temperature range:

The propulsion system shall be operable within an expected ambient temperature range of -40° to 125°F.

16. Operational life:

The mean operational life of the propulsion system should be approximately equal to that of the present spark-ignition engine. The mean operational life should be based on a mean vehicle life of 105,000 miles or ten years, whichever comes first.

The design lifetime of the propulsion system in normal operation will be 3500 hours. Normal maintenance may include replacement of accessable minor parts of the propulsion system via a usual maintenance procedure, but the major parts of the system shall be designed for a 3500 hour minimum operation life.

The operational life of an engine shall be determined by structural or functional failure causing repair and replacement costs exceeding the cost of a new or rebuilt engine. (Functional failure is defined as power degradation exceeding 25 percent or top vehicle speed degradation exceeding 9 percent).

17. Noise standards: (Air conditioner not operating)

a. Maximum noise test:

The maximum noise generated by the vehicle shall not exceed 77 dbA when measured in accordance with SAE J986a. Note that the noise level is 77 dbA whereas in the SAE J986a the level is 86 dbA.

b. Low speed noise test:

The maximum noise generated by the vehicle shall not exceed 63 dbA when measured in accordance with SAE J986a except that a constant vehicle velocity of 30 mph is used on the pass-by, the vehicle being in high gear or the highest gear in which it can be operated at that speed.

c. Idle noise test:

The maximum noise generated by the vehicle shall not exceed 62 dbA when measured in accordance with SAE J986a except that the engine is idling (clutch disengaged or in neutral gear) and the vehicle passes by at a speed of less than 10 mph. The microphone will be placed at 10 ft. from the centerline of the vehicle pass line.

18. Safety standards:

The vehicle shall comply with all current Dept. of Transportation Federal Motor Vehicle Safety Standards. Reference DOT/HS 820-083.

19. Reliability and maintainability:

The reliability and maintainability of the vehicle shall equal or exceed that of the spark-ignition automobile. The mean-time-between failure should be maximized to reduce the number of unscheduled service trips. All failure modes should not represent a serious safety hazard during vehicle operation and servicing. Failure propagation should be minimized. The power plant should be designated for ease of maintenance and repairs to minimize costs, maintenance personnel education, and downtime. Parts requiring frequent servicing shall be easily accessable.

20. Cost of ownership:

The net cost of ownership of the vehicle shall be minimized for ten years and 105,000 miles of operation. The net cost of ownership includes initial purchase price (less scrap value), other fixed costs, operating and maintenance costs. A target goal should be to not exceed 110 percent of the average net cost of ownership of the present standard size automobile with spark-ignition engine as determined by the U.S. Dept. of Commerce 1969-70 statistics on such ownership.

APPENDIX B

Engine Sizing and Selection

Power Requirements - The performance requirements of a 4000 pound car meeting the Office of Air Programs design goals (see Appendix A) can be translated into road power demands vs. vehicle speed as shown in Figure 2.1. Certain simplifying assumptions must be made to fully describe the details by which the various maneuvers are to be accomplished. For example, the DOT highway pass can be performed by assuming an infinite number of acceleration-time schedules. The shape of the peak power-speed curve will therefore vary according to the assumptions; however, for reasonable performance it appears the power train should be capable of supplying a short term power burst in excess of 115 hp at part vehicle speed and sustained road load of 65 hp at 85 mph.

The internal combustion engine must be sized to provide steady 85 mph level road cruise with full automotive comfort and convenience devices. Allowing for power train inefficiencies and accessories the engine must be capable of at least 81-85 mph continuously.

During urban operation, various engine operating schedules can be assumed to insure the vehicle can meet all the acceleration and cruise requirements yet maintain a fully charged battery. Of all the techniques, constant engine power operation offers simplicity of control and minimizes throttle changes which place more severe carburetion demands on the engine.

Previous analyses(1), supported by the simulation results of this study suggest that engine power levels of 10-20 hp are required for urban operation. The need to swing the engine power over perhaps 4:1 to 8:1 power range places some speed constraints on engine operation. Figure B-1 shows that the fuel consumption of a typical engine at constant speed varies rapidly with engine speed. Low horsepower-high economy is best accomplished by running the engine at intermediate throttle and modest rpm. Higher throttle levels at lower speed tend to increase the emissions of oxides of nitrogen (NO_x); low throttle levels at high speed increase engine pump work and result in poorer fuel economy.

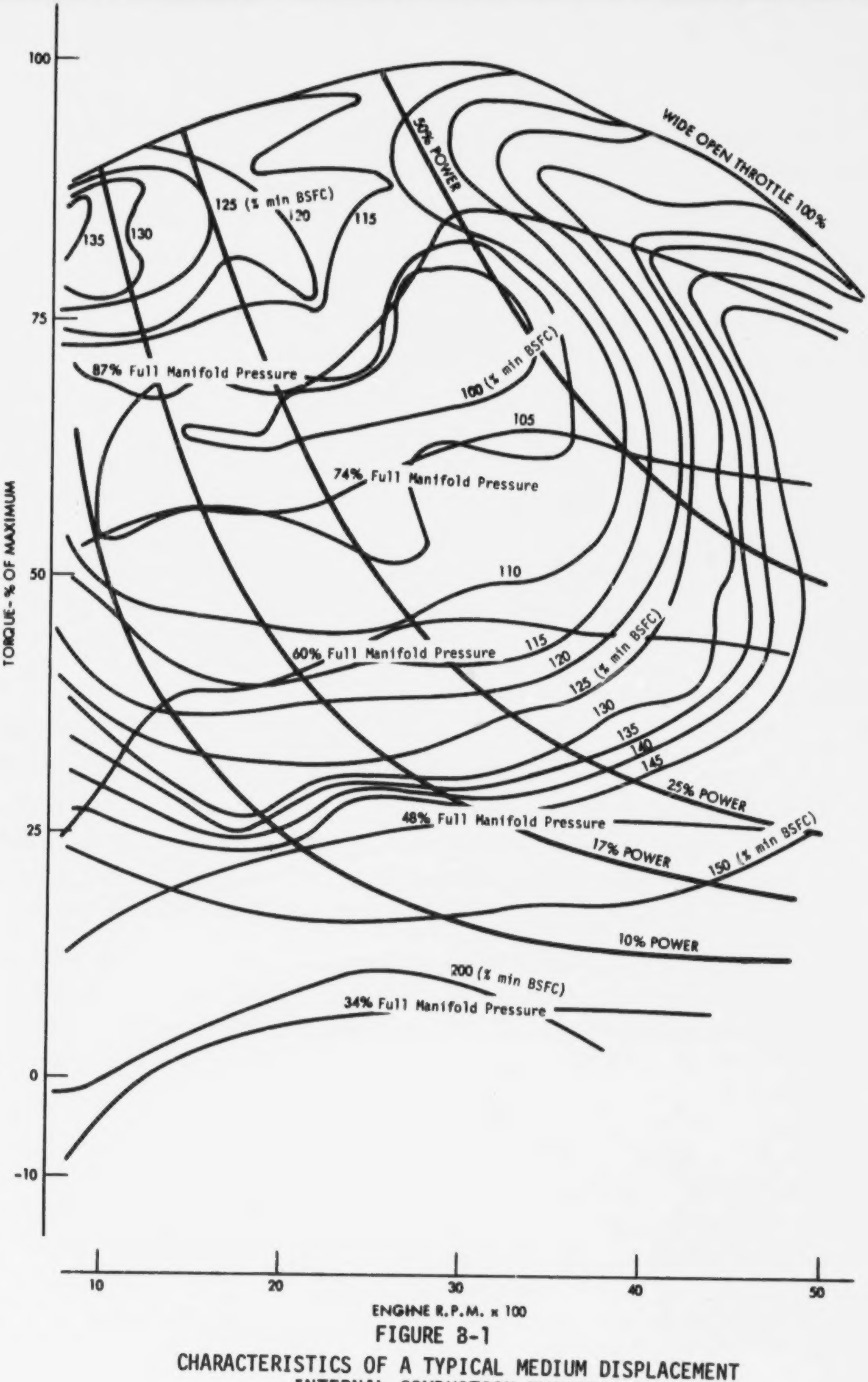

FIGURE 8-1

CHARACTERISTICS OF A TYPICAL MEDIUM DISPLACEMENT INTERNAL COMBUSTION ENGINE

Peak power on the other hand will be delivered at full throttle, at higher speeds where the effects of engine frictional horsepower, spark timing and flame speed limitations and volumetric efficiency have not yet started to decrease the net output.

Based on all these factors it appears that an engine of approximately 150 cubic inches displacement, compression ratio of around 8.0-8.5, operating over a 3:1 speed range is required.

Engine Selection Criteria

In reviewing the spectrum contemporary internal combustion engines the following selection guidelines were established:

- 120 to 160 cubic inch displacement to provide peak power without excessively high rpm and poor fuel economy at part load.
- Desirability of four cylinder in-line design rather than six cylinder to minimize cylinder-to-cylinder mixture ratio variations.
- Ability to run on nonleaded gasoline.
- Combustion chamber with low surface area-to-volume ratio.
- Absence of major exhaust emission control systems such as exhaust manifold thermal reactors, manifold air injection systems and EGR.
- Simple carburetion.
- Light weight, low volume and compact envelop.
- Water cooled design to minimize sound level.

Numerous domestic and foreign manufacturers were contacted and data on engines currently in production was solicited. Very favorable responses were received from Toyota, Nissan (Datsun), Ford, Chrysler and General Motors.

After reviewing the manufacturers' data and assessing the availability of engines in terms of the time framework of the program, it was decided that the Chevrolet Vega 2300 cc (140 CID) engine would be a reasonable choice. The engine reportedly produces 90 hp, slightly less power than may ultimately be required. The Vega uses a lightweight, aluminum block construction and has a partial hemispherical combustion chamber design for low surface-to-volume ratio. Members of the Chevrolet engineering staff

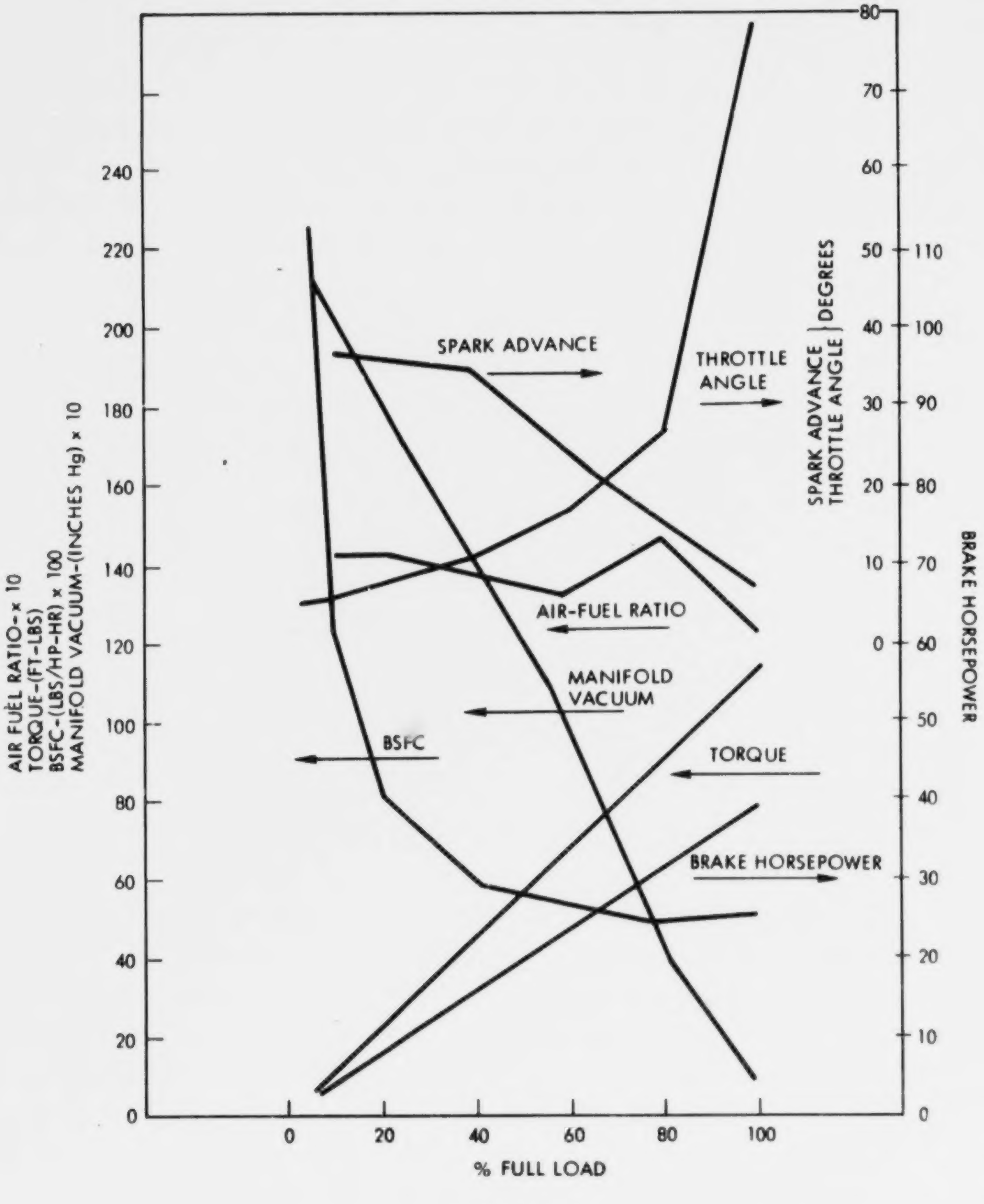

FIGURE B-2

CHARACTERISTICS OF 1971 CHEVROLET VEGA ENGINE AT 1800 RPM stated that the engine should be capable of at least 16,000 miles of wide open throttle operation without excessive value seat or face wear. Characteristics of the engine around the basic EMT operating speed of 1800 rpm are to be found in Figure B-2.

APPENDIX C

Characterization and Preliminary Performance Computations of Candidate Series Systems

The three series systems chosen as candidates were analyzed to determine their efficiencies, weight, relative cost and complexity.

This appendix contains a summary outline of the preliminary designs and specifications of each system as well as sample computations showing how each of the candidates were evaluated. The open circuit battery voltage was assumed to be 400 VDC in these preliminary computations as it was felt that this voltage would press the conventional limits of machine and semiconductor technology while giving lower ohmic and solid state losses. Latter considerations of battery reliability, machine cost, etc. suggested a lower voltage and 240 VDC was subsequently adopted for the computer simulation. While there was a change in operating voltage it is felt that the results of these preliminary studies are still valid at the lower voltage.

Computation of Preliminary Machinery and PCU Ratings for the Candidate Series System Hybrid Power Trains

The rationale and computations for specifying the alternators, traction motors and respective PCUs are outlined below for the three candidate series systems. The block diagrams of the systems can be found in Figures 2.2, 2.3 and 2.4.

Full Voltage Series Power Train

1. Maximum continuous road load is 65 hp = 48.4 kw at 85 mph cruise.

2. Assume the efficiency of the motor at rated power and speed is approximately 90%. Nominal motor voltage will be approximately 360 V; nominal current is 149 A.

3. The PCU must be rated for 54 kw. The battery voltage assumed for the system is 400 V.

4. The PCU must have overload and commutation capability to satisfy road demand.

From Figure 2.5 it can be seen that maximum motor torque equal to 4.14 times rated torque will be required at 30 mph. Thus, the PCU must have a maximum equivalent commutation rating of 4.14 x 149 = 616 A. The KVA rating of the PCU is therefore 272.

5. Poorest efficiency of the PCU at 272 KVA is assumed to be 94%.

6. The maximum power output of the rectifier must be $\frac{54}{.94}$ = 57.5 kw.

7. The rectifier efficiency is $\frac{397}{400}$ = 99.2.

8. The power required from the alternator is $\frac{57.5}{0.992}$ = 58 kw. The rating of the alternator at top speed therefore is 3 x 58 = 174 kw. The rating is multiplied by 3 to reflect the one-third field utilization in urban operation.

9. The alternator supplies six step current waveforms. The form factor impact on the alternator is assumed to be one thus the alternator is rated at one-third speed at 81 KVA; at top speed it is 183 KVA.

10. The alternator efficiency at top engine speed and road power is assumed to be 90%.

11. The peak input power to the alternator must be 64.5 kw and the total system efficiency at top speed is 75.5%. These computations assumed a forced cooled alternator and are summarized in Table 2.1. These computations were done also for an oil sprayed alternator and are summarized in Table 2.2.

Two-Generator Series Power Train

1. Maximum continuous road power is the same as the full voltage system.

2. Motor efficiency is 90% at rated power, input power is 54 kw.

3. The PCU will have the same commutation capability as the PCU of the full voltage system, i.e., 272 KVA, but a thermal rating of 20 kw. The 20 kw value was obtained from experimental test runs of the EMT system on the LA cycle. Note that during cruise conditions the PCU in this case does not handle motor power.

4. Rectifier #2 is required to deliver 54.5 kw to the series choke. The choke's efficiency is 99%.

5. Alternator #2 output will be $\frac{54.5}{.992}$ = 54.8 kw. The p.u. rating at top speed of alternator #2 is 1.5.

6. Alternator #1 is rated for the power setting of the engine operating in urban traffic required to maintain the battery charged over a driving cycle. Using data from EMT tests the rating of alternator #1 and rectifier was chosen to be 10 kw for this computation.

7. Alternator efficiency for forced cooled system is assumed to be 90%. Form factor impact due to rectification is 1.05.

8. Input into two alternator system is therefore $\frac{54.8}{.87}$ = 63.0 kw (η = 87% is used as the combined operating efficiency over an average LA-4 cycle alternators).

9. Total system efficiency is 77%.

The above computations assumed a forced cooled machine and are summarized in Table 2.3 and repeated for an oil spray-cooled machine as shown in Table 2.4.

Series System with Boost PCU

1. Maximum continuous motor load and efficiency is the same as the full voltage system.

2. Motor PCU considerations are the same as those for the full voltage system.

3. The Boost PCU output is the same as the rectifier output of the full voltage system, 57.5 kw.

4. Boost PCU is 94% efficient; rectifier is 99% efficient.

5. The alternator efficiency is assumed to be 90% at full load.

6. Alternator KVA rating due to form factor impact is 1.05 x 6.16 = 64.6 KVA.

7. Input into alternator is therefore $\frac{61.6}{.90}$ = 68.5 kw.

Total system efficiency for forced cooled alternator is 71%. The above computations are summarized in Table 2.5 for a forced cooled alternator and in Table 2.6 for an oil spray-cooled alternator.

Full Voltage System Under Hybrid Conditions

A. Computations for mean maximum demand of 22 kw (29.5 hp) at 21 mph

1. Motor torque demand at 1/4 rated speed $\frac{29.5}{65} \times 4 = 1.82$ p.u.

2. Motor average efficiency at 1.82 p.u. torque and 1250 rpm is 76%. Current p.u. value is 1.65.

3. Motor power input is thus $\frac{22}{.76} = 29.0$ kw.

4. The PCU's full rating is 54 kw and 272 KVA. The PCU will deliver approximately 1.65 x 149 = 246 ADC to the motor at chopper duty cycle of approximately 33%.

5. The efficiency of the PCU at 1 kc will be between 90% to 93%; assume 90% efficiency.

6. Input into the PCU is 32.2 kw.

7. The engine input to the alternator is assumed constant and equal to 15 hp (11.2 kw). The force cooled alternator is rated at 58 kw. At 11.2 kw input its efficiency is 55% and its output is 6.16 kw. The efficiency of the oil spray-cooled alternator is 30% and the output of the rectifier is 3.33 kw.

8. The battery contribution is therefore 32.2 - 6.1 = 26.1 kw for forced cooled alternator and 28.8 for oil spray-cooled alternator.

B. Computations for 21 mph cruise conditions

1. The motor torque demand is $\frac{3.75}{65} \times 4 = .23$ p.u., and the current required is 0.4 p.u. (60 A).

2. Motor efficiency at 0.4 p.u. current and 1250 rpm is 83%.

3. Motor input is 3.36 kw.

4. PCU efficiency is 79% to 83%; use 80%.

5. Motor power required from the alternator/rectifier is 4.20 kw into the PCU.

6. Power flow to battery is therefore 6.1 - 4.20 = 1.9 kw.

Two Alternator Scheme Under Hybrid Conditions

A. Computations for mean maximum demand

1. Motor conditions are the same as for the previous case.

2. The PCU is rated at 20 kw and 272 KVA. The PCU has approximately the same duty cycle and load as before because the contributions from alternator #2 are small compared to the total PCU input power.

3. The PCU efficiency is taken at 90%.

4. The engine input to the alternators is 15 hp. Alternator #2 is rated 54.8 kw and by trial and error its efficiency is determined to be 67% for the forced cooled alternator.

5. Rectifier #2 output is 7.5 x .970 = 7.26 kw.

6. The choke current at 360 x 118 V is approximately 60 A. Choke efficiency is approximately $\frac{7.45}{7.450+436}$ = 94.5%. Choke losses are 548-112 = 436 w.

7. Choke output is 7.26 x .94 = 6.86 kw.

8. The power required from the PCU is 29.0 - 6.86 = 24.14 kw.

9. This power required from the battery is $\frac{24.14}{.9}$ = 26.8 kw.

B. Computations for cruise 21 mph conditions

1. Motor torque demand is as before.

2. Alternator #2 delivers 3.36 kw to the motor terminals through rectifier #2 and the choke.

3. The choke efficiency is:

$$\frac{3.36}{3.36+436} = 87.5\%$$

4. The output from rectifier #2: $\frac{3.36}{.875}$ = 3.84 kw.

5. The output from alternator #2: $\frac{3.84}{.97}$ = 3.87 kw.

6. The efficiency of alternator #2, at $\frac{3.87}{54.8}$ = 7.1% load, is 57.5%.

7. The input into alternator #2 is $\frac{3.87}{.575}$ = 6.75 kw.

8. The input into alternator #1 is therefore 11.2-6.75 = 4.45 kw.

9. The efficiency of alternator #1 is 66%.

10. The output of alternator #1 is 4.45x.66 = 2.94 kw.

11. The charge available for the battery is 2.94x.992 = 2.81 kw.

Series System with Alternator PCU Under Hybrid Conditions

A. Efficiency calculation for mean maximum demand

1. The alternator accepts 11.2 kw. Trial and error gives 60% efficiency at this level.

2. The alternator output is 11.2x.6 = 6.7 kw.

3. The Boost PCU at about 10% of its rated current is approximately 79%. Its current is 60 amperes.

4. The Boost PCU output is 6.7x.79 = 5.3 kw.

5. The battery drain is 32.2-5.3 = 26.9 kw.

B. Computations for 21 mph cruise conditions

1. The alternator input is 11.2 kw and its output is 6.7 kw.

2. The output of the Boost PCU is 5.3 kw.

3. The charge available for the battery is 5.3-4.2 = 1.1 kw.

APPENDIX D

Characterization of Motors and Generators for Series and Parallel Systems

Rotating machines for the candidate series and parallel systems were selected after preliminary analyses of the systems. Initial specifications were based on estimates of peak, average and RMS levels of operation; computer-generated data has supported many of the specifications.

Full Voltage Series System Machine Specifications

The traction motor is a DC series type machine rated at 65 hp at top vehicle speed. The selected motor is similar in size and construction to GE's motor frame, CD 280/250B. The machine's top speed is 4650 rpm and it weighs approximately 325 pounds. Although a higher speed motor such as common in aerospace applications will weigh less, the top speed rating in automotive application must be more conservative because of mechanical, electrical and cost considerations. Mechanical limitations include brush and commutator wear, brush bounce, brush pressure, centrifugal force, etc. Electrical limitations include commutation capability, efficiency, etc. The high specific motor weight of .2 hp/lb is the best expected within the present state-of-the-art.

The motor characteristics are shown below in Table D-1.

TABLE D-1

SERIES HYBRID TRACTION MOTOR

Motor type------------------------------series DC
Horsepower (hp)-------------------------65 at rated speed
Rated speed (rpm)-----------------------4650
Terminal voltage (volts)----------------235
Input current (amps)--------------------235 at rated torque
Rated torque (lb-ft)--------------------74
Duty------------------------------------Continuous
Frame-----------------------------------Similar to GE CD 280/250B
Diameter (inches)-----------------------12 1/2

TABLE D-1 (Cont'd)

Length, less shaft (inches)	21
Approximate weight (lb)	325
Ambient temperature, operating (^{o}C)	-30 to +50
Overspeed (rpm)	150% of rated speed
Brush life	50,000 car miles between changes
Cooling requirement, forced ambient air	200 CFM at 1.6" H_2O, $50^{o}C$ maximum

Series Hybrid Motor Performance

Basic performance characteristics of the series system motor were supplied by motor manufacturers. Because the vehicle requirements include power and torque levels for above and below rated conditions, it was necessary to calculate performance at off-design demands. Computations were made at 14 current values for differing terminal voltage. Six terminal voltages were selected to represent machine operating conditions. They were approximately equally spaced from 50 volts to 280 volts. Figure D-1 shows the results of those computations.

The machine's efficiency, η_M, was computed as a function of current and speed to facilitate the overall system computer model. The design specifications of Table D-1 were used to compute the efficiency. Figures D-2 and D-3 present machine efficiency for various speeds and current levels; two figures are used for the sake of clarity.

The performance characteristics of Figures D-1, D-2 and D-3 are used in the overall system program as indicated in Appendix F. Wherever necessary the computer performs an interpolation fit of the data to values not shown in the figures.

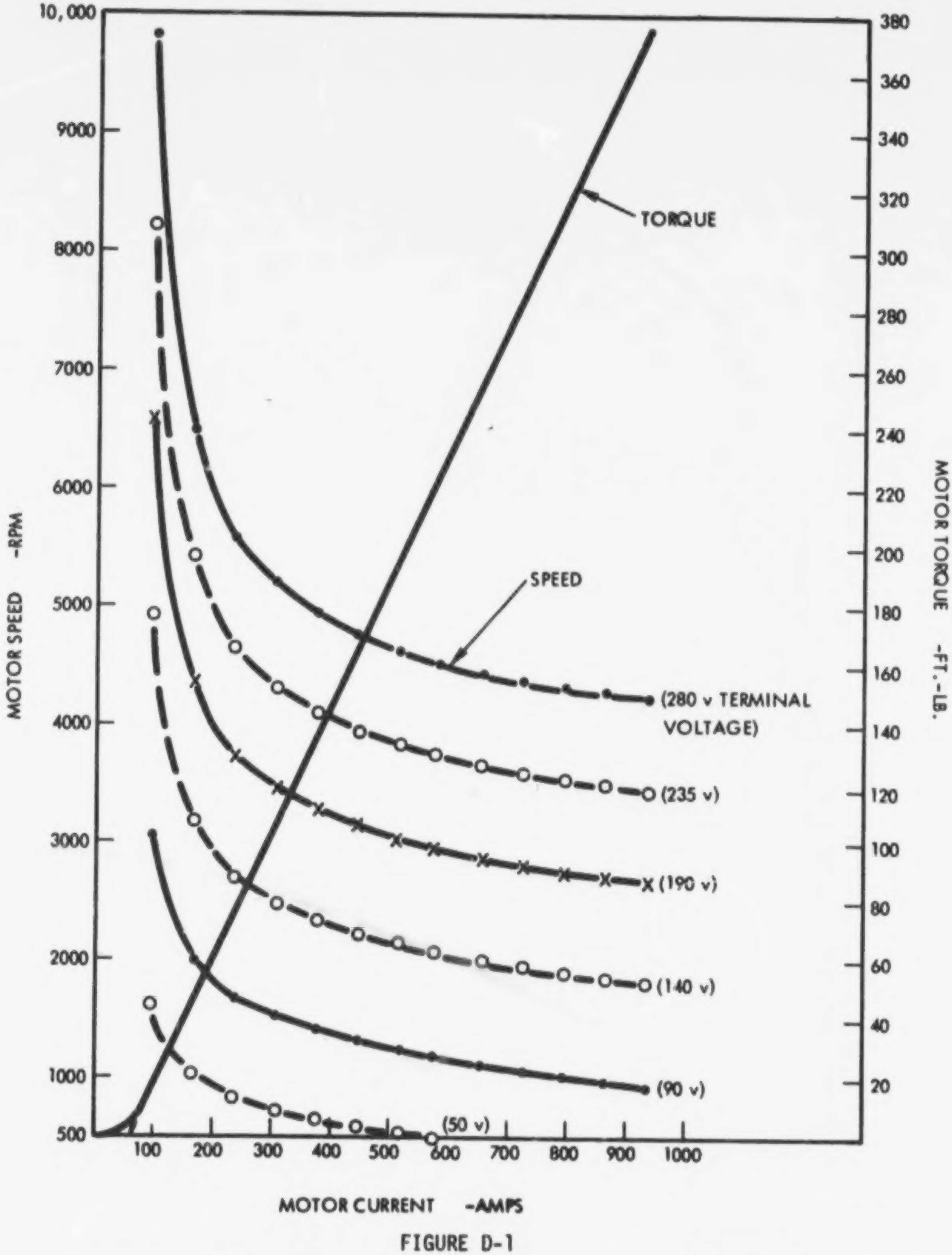

FIGURE D-1

CHARACTERISTICS OF MOTOR FOR SERIES SYSTEM

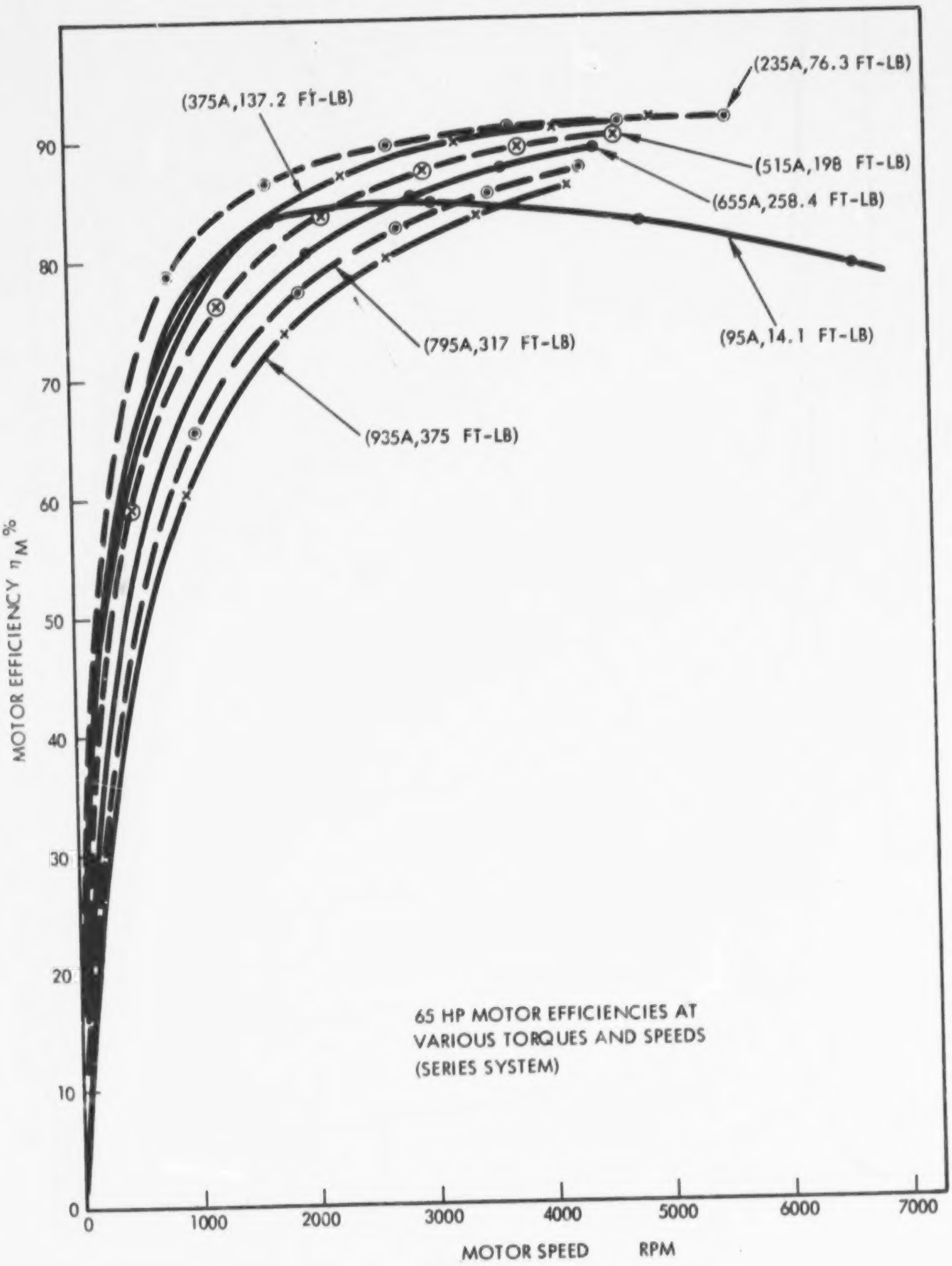

FIGURE D-2

SERIES SYSTEM MOTOR EFFICIENCY

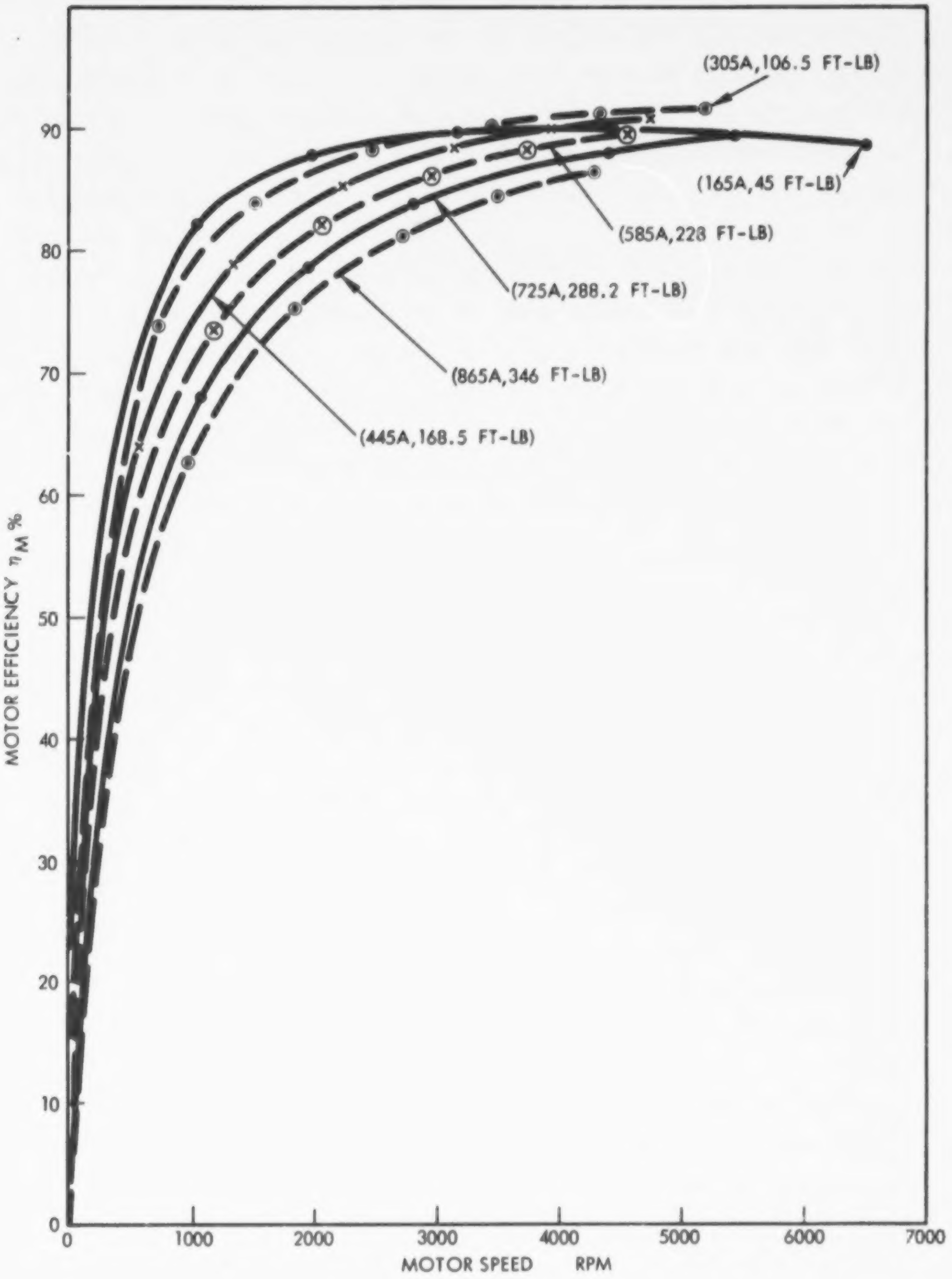

FIGURE D-3

SERIES SYSTEM MOTOR EFFICIENCY

Motor Characterization for the Parallel System

The traction machine selected for the parallel system is of the DC series type, rated at 30 hp at 7200 rpm and 180 volts. It is possible to operate the motor for the parallel system at a higher speed than the motor for the series system because of the smaller size and smaller diameter of the armature and commutator. There can be some question as to the advisability of using a machine with so low a rated torque in view of the need for the motor to provide accelerating torques several times in excess of rated torque. TRW's experience with the breadboard EMT system, manufacturers' data and the low probability of high torque events suggests that with proper gearing the parallel system motor need only possess about a 300% peak torque capability. This specification is definitely within bounds of conservative design. Further analysis of machine ratings based on computer simulations can be found in Section 5.4.

The motor characteristics for the parallel hybrid system are found in Table D-2.

TABLE D-2

PARALLEL HYBRID TRACTION MOTOR

Motor type------------------------------series DC
Horsepower (hp)-------------------------30 at rated speed
Rated speed (rpm)-----------------------7200
Terminal voltage (volts)----------------180 V
Input current (amps)--------------------145 at rated torque
Rated torque (lb-ft)--------------------22.5
Duty------------------------------------Continuous
Frame-----------------------------------similar to GE BT 2348
Diameter (inches)-----------------------9
Length, less shaft (inches)-------------15 1/2
Approximate weight (lb)-----------------150
Ambient temperature, operating (^{o}C)----- -30 to +50
Overspeed (rpm)-------------------------150% of rated speed
Brush life------------------------------50,000 car miles between changes
Cooling requirement, forced ambient air------------------------------------120 CFM at 1.0" H_2O, 50^{o}C maximum

Parallel Hybrid Motor Performance

Motor performance characteristics were generated in a manner similar to those of the series hybrid motor. Calculations were made at eleven current levels for each of six terminal voltage points to give a wide range of operating conditions from overload to near-idling.

Figure D-4 shows the armature current and the relationship between developed torque and armature current. Figure D-5 shows the relationship of motor speed and voltage at various torque values. Figure D-6 presents the motor efficiency as a function of speed and armature current.

Generator Characterization for the Full Voltage Series System

The alternator's nominal rating of 58 kw is based on providing cruise power to the traction motor at vehicle top speed. From EPA guidelines, a top operating speed of 12,000 rpm was used; however, arguments relative to heat engine speed, power and economy limitations (see Appendix B), coupled with the need to provide a quasi-constant alternator output voltage over the complete vehicle speed range cause a change in rating. The basic machine voltage rating must be established at 4000 rpm to supply a nominal rectifier voltage of 240 VDC. The output of the alternator must be rectified and waveform losses caused by the full wave bridge rectifier will increase the machine's KVA rating to 61 KVA.

Either Lundel or salient pole type machines could be modeled. It is generally assumed that the Lundel machine will be less expensive to construct. However, recent studies performed by Westinghouse Electric, suggest that the salient pole machine may have a slightly higher efficiency, lower weight and lower stator fabrication cost. Further tradeoffs will have to be made to test the validity of this judgment. Based on the high probability that the salient pole type will be a better choice, the modeling and computations are based on it.

The efficiency of an alternator is load and speed dependent. The impact of speed on efficiency is heavily affected by the mechanical design of the machine. It is reasonable to expect that windage losses will go up with speed. Similarly the generator load will increase as the generator speed increases with vehicle speed and thus the ratio of windage

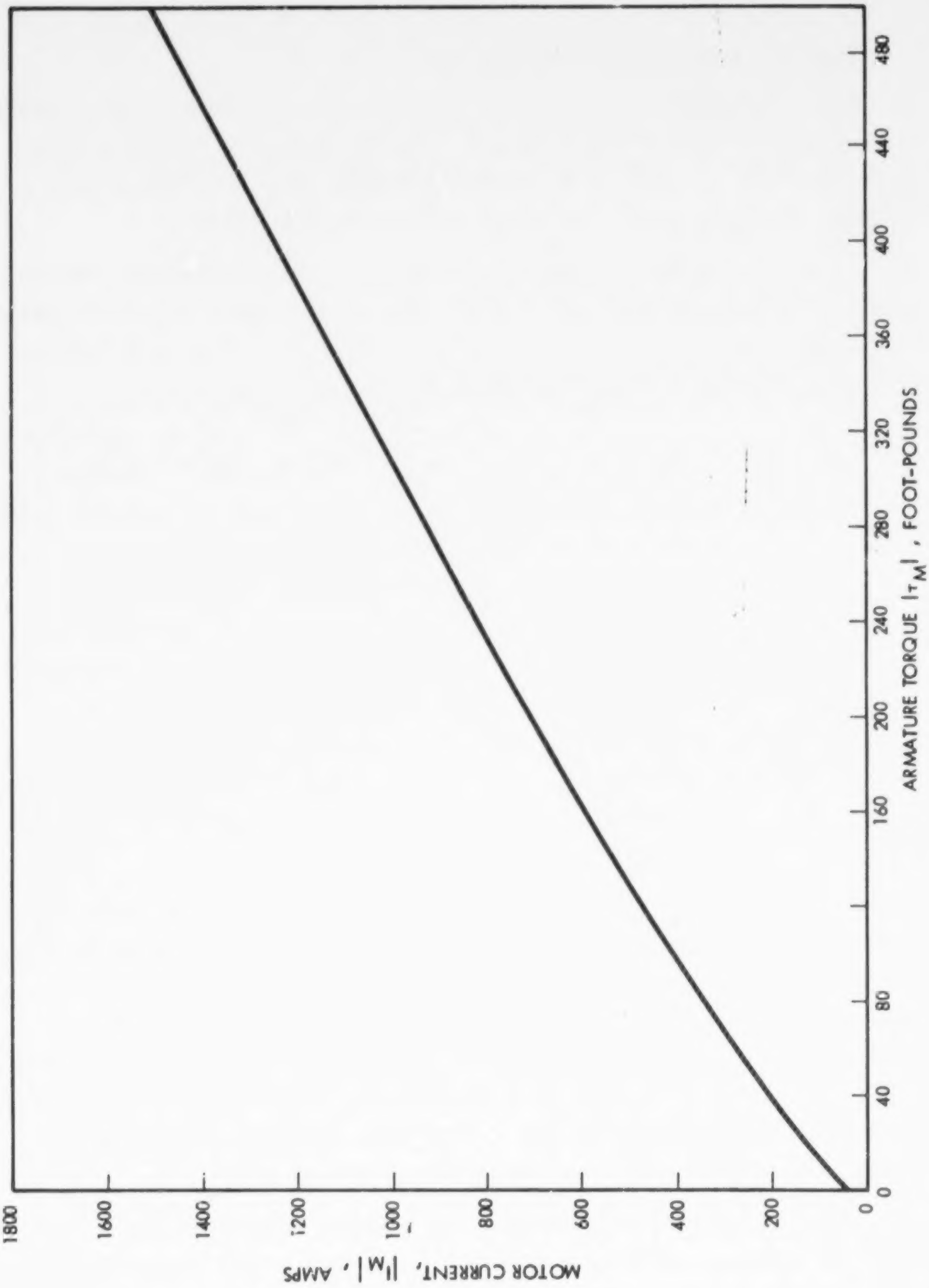

FIGURE D-4

TORQUE OF THE PARALLEL SYSTEM MOTOR

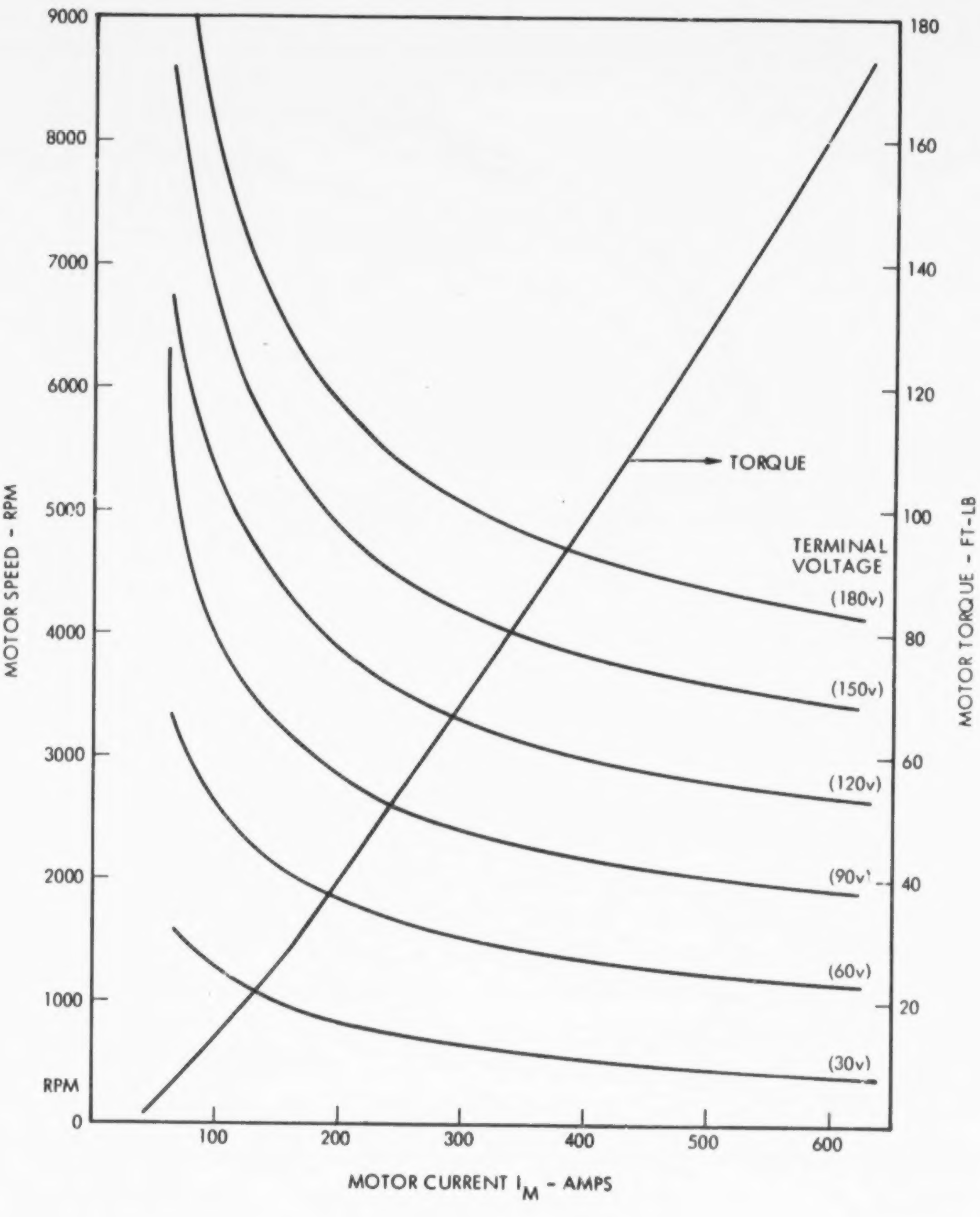

FIGURE D-5

CHARACTERISTICS OF MOTOR FOR EMT SYSTEM

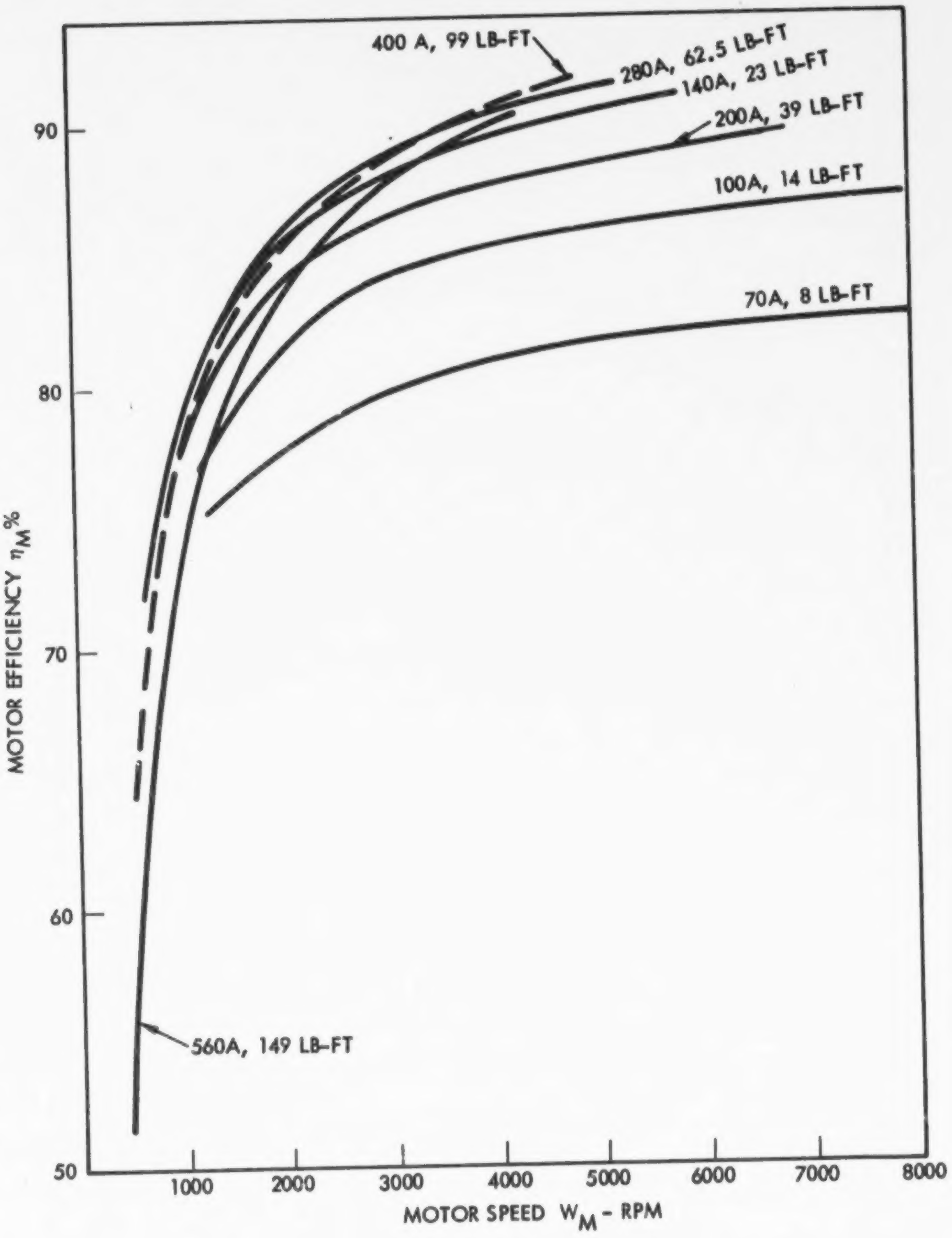

FIGURE D-6

EFFICIENCY OF MOTOR FOR EMT SYSTEM

losses to output will tend to remain constant. Magnetic losses will either decrease or remain fairly constant because the air gap flux is reduced inversely proportional to speed. Copper losses, at any current level, will increase with speed due to skin effect, but over the 133 to 400 Hz range which is expected in service, this effect is second order and is probably compensated for by the fact that the previously mentioned magnetic losses will tend to diminish. Thus, it can be seen that in the context of the full voltage series system and its mode of operation, alternator windage is the only loss component which varies with speed and must be accounted for.

The windage component must of necessity be quite small in a 12,000 rpm machine possessing high efficiency at top speed and load. We estimate windage contributes no more than 3% to the total 7% loss of the machines we have studied. Furthermore, to a first order of approximation, it is practical to assume that the efficiency of the alternator will vary only slightly with speed. This latter assumption has been borne out by checking representative design of GE and Westinghouse. Finally, as previously stated the hybrid system constricts the alternator to one unique load level for each road speed, i.e., in urban traffic the alternator operates at 4000 rpm and in highway traffic its load is proportional to road load and its speed increases proportionally with the engine speed. A single curve of efficiency vs. input power which incorporates adjustments due to speed, may be used to characterize this alternator. Such a curve is shown in Figure D-7.

The mechanical design of the machine will be a composite of designs which reflect long-life and low maintenance costs. To provide ready access, each of the two field supply slip rings would be located on each end of the rotor. This also allows commonality for economical end bell construction. No frame is provided for the stator stack and the end bells are thru-bolted together with the stack allowing for a low total weight. The rolling element bearings will have a life of 30,000 hours and the life of the slip ring brushes will be good for at least 50,000 car miles, but not less than 2500 hours of operation.

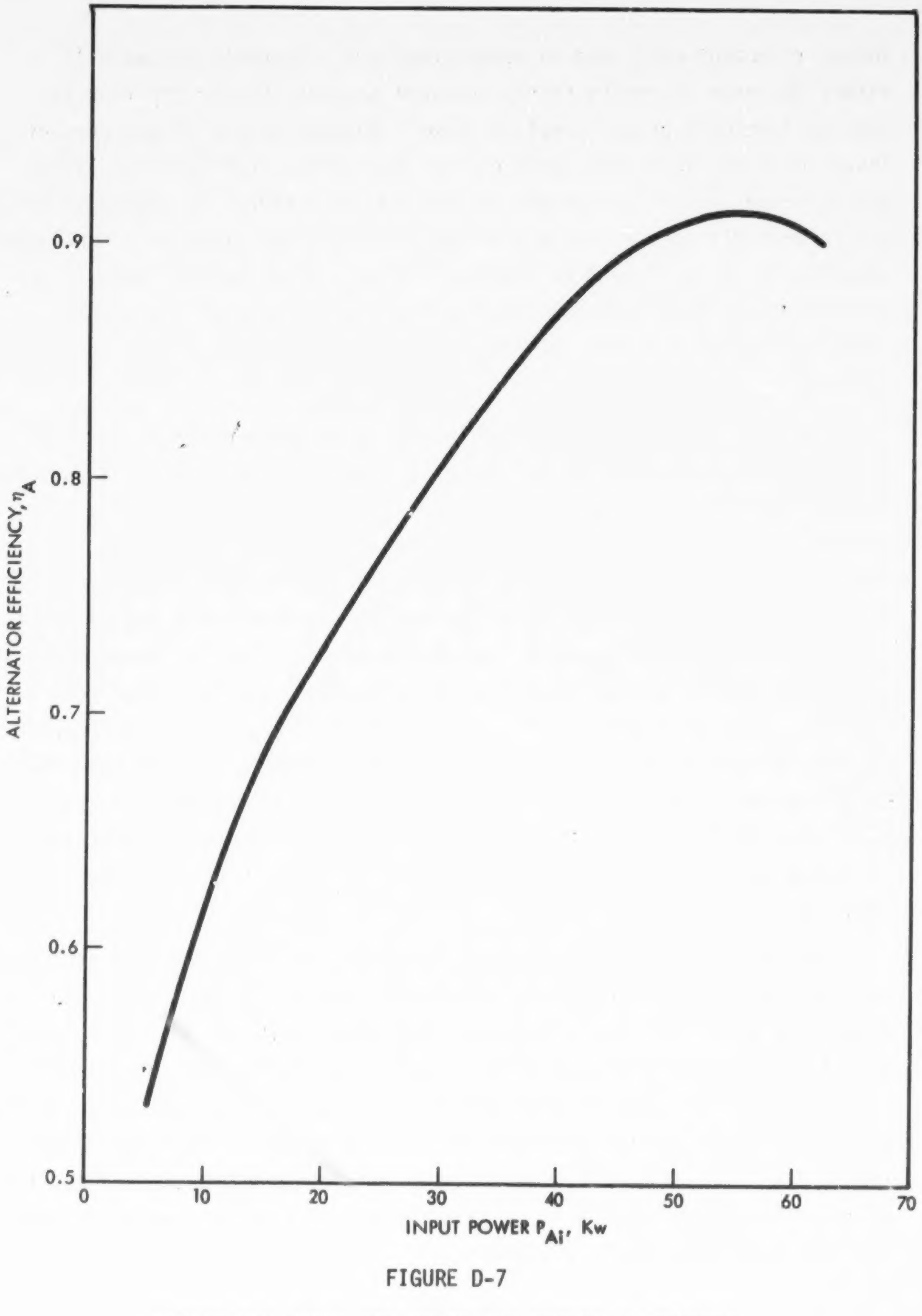

FIGURE D-7

EFFICIENCY CURVE FOR FORCE AIR COOLED ALTERNATOR
OF FULL VOLTAGE SERIES SYSTEM

TABLE D-3

FULL VOLTAGE SERIES SYSTEM ALTERNATOR-RECTIFIER CHARACTERISTICS

Alternator type	salient pole with slip rings
Rating (kw) at top speed	58 (x3)*
Base speed (rpm)	4000
Power factor	.95
Rectifier voltage (nominal)-VDC	240
Speed range at nominal voltage (rpm)	4000 to 12,000
Overspeed (mechanical)	150% of rated speed
Number of phases	three
Frequency at top speed (Hz)	400
Duty	continuous
Ambient temperature, operating (^{o}C)	-30 to +50
Weight (lb)	160
Diameter, approximately (inches)	10.0
Length, approximately (inches)	19.0
Brush life, between changes	50,000 car miles
Cooling requirement with specified load schedule	integral fan

---

*58 kw rating is available at base speed, top speed rating is available but never used.

TABLE D-4

TYPICAL ALTERNATOR-RECTIFIER OUTPUT POWER SCHEDULE VS. SPEED FOR EMT

Output Power (kw)	Alternator Velocity (rpm)
9.9235+00	4000
9.9235+00	4000
9.9235+00	4000
9.9235+00	4000
9.9235+00	4000
9.9235+00	4000
9.9235+00	4000
9.9235+00	4000
1.4667+01	4000
1.7855+01	4940
2.1469+01	5881
2.5788+01	6822
3.0844+01	7763
3.6637+01	8705
4.3151+01	9646
5.0396+01	10,587
5.8699+01	11,528
6.8043+01	12,469

TABLE D-5

PARALLEL SYSTEM ALTERNATOR-RECTIFIER CHARACTERISTICS

Alternator type	salient pole with slip rings
Rating at base speed (kw)	10 kw
Base speed (rpm)	12,000
Top speed	equal to base speed
Power factor	.95
Maximum rectified voltage (volts)	200 at base speed and rated load
Speed range (rpm)	1200 to 12,000
Overspeed (mechanical)	150% of base speed
Number of phases	three
Frequency at base speed (Hz)	400
Duty	continuous
Ambient emperature, operating (^{o}C)	-30 to +50
Weight (lb)	40
Diameter, approximately (inches)	8"
Length, approximately (inches)	4"
Brush life, between changes	50,000 car miles
Cooling requirement, forced ambient air	100 CFM at 1.0" H_2O
Suggested field voltage (VDC)	200

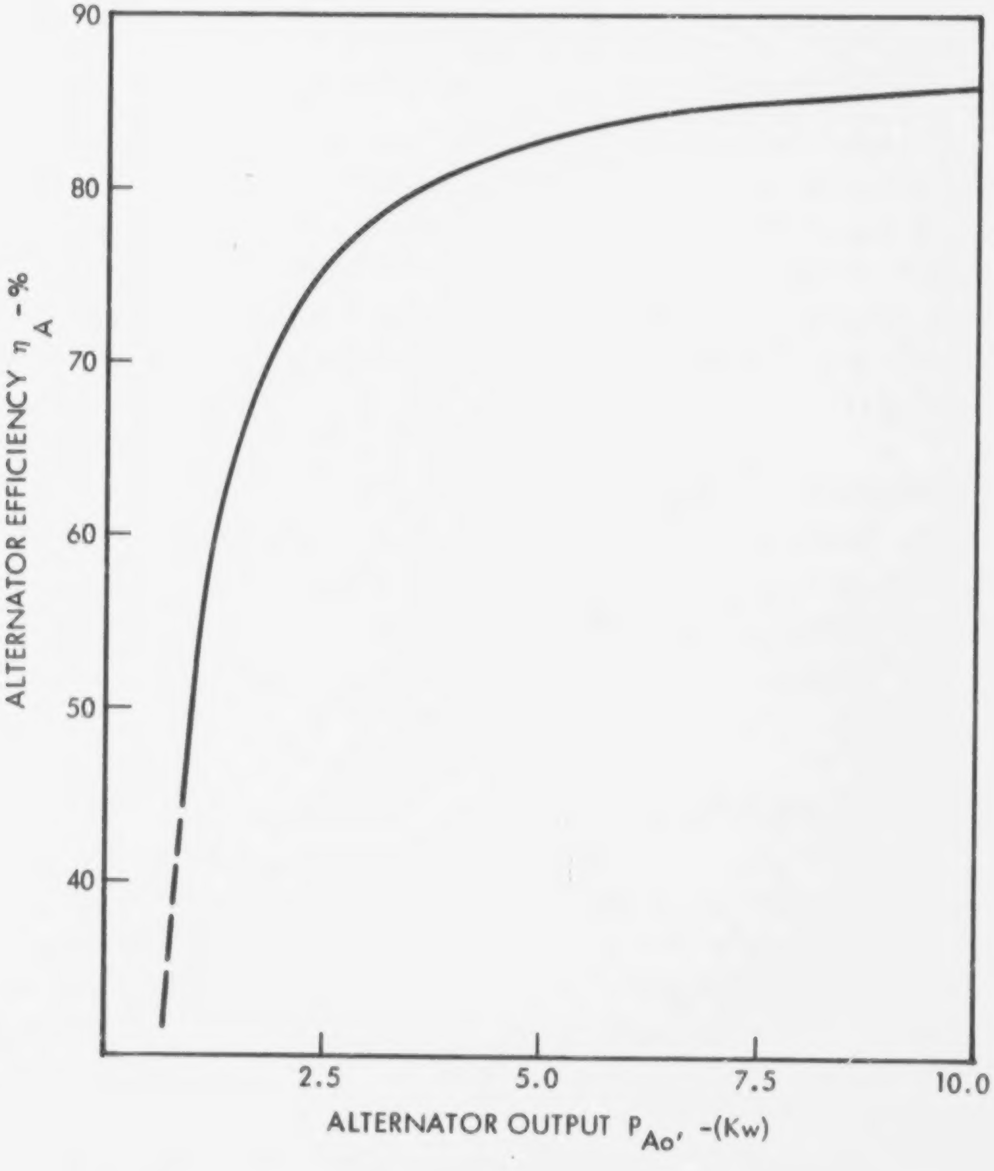

FIGURE D-8
EFFICIENCY CURVE FOR 10 KW, 12,000/1200 RPM
FORCED COOLED, 40 LB ALTERNATOR

APPENDIX E

PCU Efficiency Models

The power circuitry shown schematically in Figure E-1 is assumed to be used to control the power flow between the battery bus and the traction motor in either the series or parallel hybrid systems. The circuit can operate as a chopper to process motor drive power or as a boost PCU to process motor regenerative power back to the battery.

The power losses in the PCU are divided into four categories, each dependent on one or both of the primary variables; motor input (output) current, I_M, which is the same as the PCU output (input) current and α, the ratio of the time that current flows through the PCU to the total period time, T. In the PCU model the chopper frequency is assumed constant and thus frequency effects are not incorporated into the equations as variables.

Loss Category 1: Commutation Oscillation

The current flows in path C_c, SCR2, CR3, L_c and back to C_c. This loss is a function of the voltage to which C_c had charged and circuit Q which is considered constant for this circuit. The loss assigned to the oscillation portion of the cycle is essentially independent of load and duty cycle.

Loss Category 2: Recharge of C_c

Recharge current flows through the battery in path, CR2, C_c, SR, L_F, motor armature and back to the battery. The losses in the PCU are due to the drop in CR2, C_c and SR. This essentially is a constant current recharge of C_c from $-V_{Cc}$ to $+V_{Cc}$. From the previous discussion $+V_{Cc}$ is assumed constant, therefore, $-V_{Cc}$ is also constant since the oscillation which produces $-V_{Cc}$ is only dependent on the "Q" of the path described in Category 1. The dissipation in C_c and SR during the recharge are functions of I_M and not I_M^2, since the amp-sec to recharge a capacitor over a fixed ΔV is constant. Thus, the losses in the diode CR2 are constant.

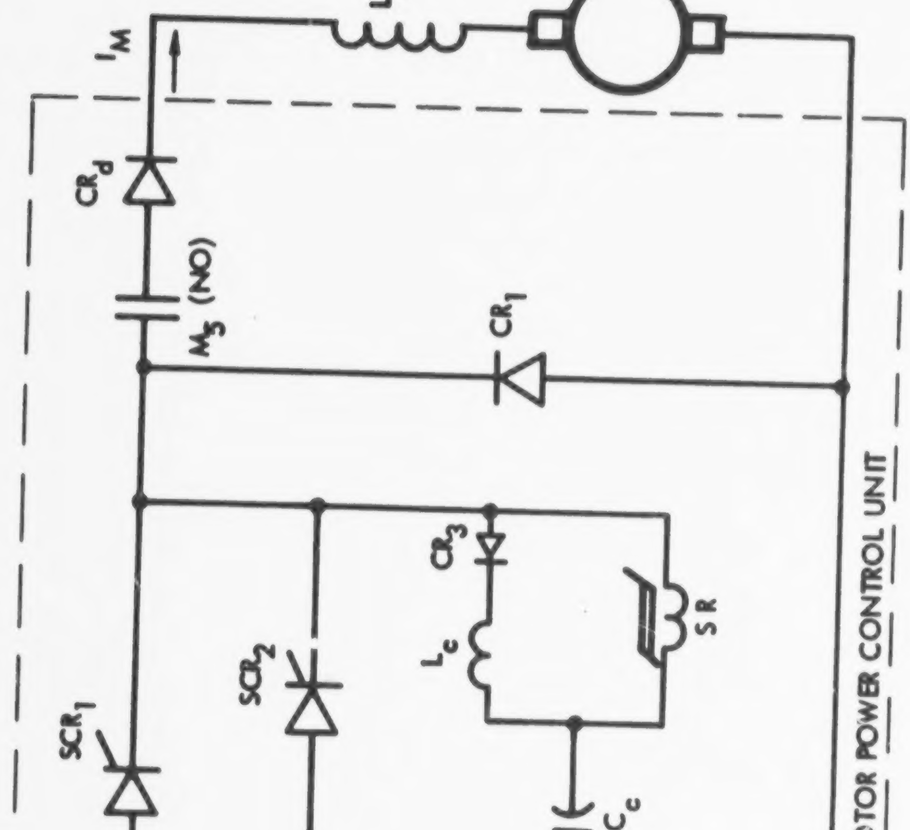
I_M
L_{field}
CR_d
M_5 (NO)
CR_1
SCR_1
SCR_2
CR_3
L_c
SR
C_c
CR_2
MOTOR POWER CONTROL UNIT
I_{PCU}
$R_{BATTERY}$
V_{Bi}
+

FIGURE E-1
MOTOR PCU USED IN SERIES AND PARALLEL MODELS

Loss Category 3: Main Power Handling Elements (SCR1, CR1)

During its conduction time, SCR1 passes the current I_M to the load. During the short interval when category 2 loss occurs, this current will flow through CR2, C_c and SR bypassing SCR1. Following this non-conduction time the main elements in the other path through CR1 will carry the load.

Essentially then, either SCR1 or CR1 will conduct the load current, with the exception of the small increment mentioned in category 2. The loss in this latter path is approximately proportional to I_M and is only slightly modified by the conduction angle (α) since the forward drop in SCR1 is greater than CR1. The conduction angle effect lowers the total loss as the conduction time in SCR1 is reduced. Also as I_M decreases the portion of time that CR2 carries the main load increases, making category 3 losses more dependent on I_M than on α.

Loss Category 4: Drive/Regeneration Circuit through CR_d, M5NO and the Drive Motor

This circuit will reverse the current in one of the elements of the motor, thereby achieving both the drive and regeneration function. It consists of a relay and a diode. It can be assumed that the relay contacts have negligible loss, but the diode will dissipate power at all times that the output current I_M flows. This will be dependent only on diode drop and I_M.

The details of the relative contributions for each category are relatively involved and are probably beyond the scope of this report. Computations were made assuming two different current rated PCUs. A 900 ampere PCU was assumed to be required in situations where there was only a single gear ratio between the motor and driving wheels. The single ratio meant design compromises which increased the motor current during low speed-high acceleration events. The incorporation of two or more gear ratios reduced the motor torque and current demands and a lower current-rated PCU of 600 amperes could be used.

TABLE E-1

SUMMARY OF PCU LOSSES BY LOSS CATEGORY

	Category 1	Category 2	Category 3	Category 4
600 amp PCU	486 watts	$0.32\ I_M + 145$ watts	$1.5\ I_M$	$1.25\ I_M$
900 amp PCU	680 watts	$0.24\ I_M + 215$ watts	$1.5\ I_M$	$1.25\ I_M$

Motor PCU Efficiency Calculations

The PCU efficiency in drive is:

$$\eta_{PCU} = \frac{P_B - P_{L,PCU}}{P_B}$$

(η_{PCU} and η_{PCUM} can be used interchangeably since they refer to essentially similar devices; $P_{L,PCU}$ is the power loss in the PCU)

The PCU efficiency in regeneration is:

$$\eta_{PCU} = \frac{P_B}{P_B + P_{L,PCU}}$$

$P_{L,PCU}$ for the 600 A unit is:

$$P_{L,PCU} = 486 + (145 + .32\ I_M) + 1.5\ I_M + 1.25\ I_M = 631 + 3.07\ I_M$$

$P_{L,PCU}$ for the 900 A unit is:

$$P_{L,PCU} = 680 + (215 + .24\ I_M) + 1.5\ I_M + 1.25\ I_M = 895 + 2.99\ I_M$$

Thus, during drive

$$\eta_{PCU} = \frac{I_M V_{Bi}\ \alpha - I_M^2 R_B\ \alpha - 631 - 3.07\ I_M}{I_M V_{Bi}\ \alpha - I_M^2 R_B\ \alpha} \text{ for the 600 amp system}$$

$$\eta_{PCU} = \frac{I_M\ V_{Bi}\ \alpha - I_M^2\ R_B\ \alpha - 895 - 2.99\ I_M}{I_M\ V_{Bi}\ \alpha - I_M^2\ R_B\ \alpha} \text{ for the 900 amp system}$$

and during regeneration

$$\eta_{PCU} = \frac{I_M\ V_{Bi}(1-\alpha)+I_M^2\ R_B(1-\alpha)}{I_M\ V_{Bi}(1-\alpha)+I_M^2\ R_B(1-\alpha)+631+3.07\ I_M} \text{ for the 600 amp system}$$

$$\eta_{PCU} = \frac{I_M\ V_{Bi}(1-\alpha)+I_M^2\ R_B(1-\alpha)}{I_M\ V_{Bi}(1-\alpha)+I_M^2\ R_B(1-\alpha)+895+2.99\ I_M} \text{ for the 900 amp system}$$

APPENDIX F

Hybrid Vehicle Computer Modeling and Simulation

All computations of component and system performance were made at elements of a vehicle velocity-acceleration matrix. The vehicle velocity, v_R, ranged from 0 to 70 mph in 5 mph steps. The velocity for each step was assumed to be the midpoint value; thus the matrix value for the first step of 0 to 5 mph was taken at 2.5 mph while that for the final step, 65 to 70 mph, was at 67.5 mph. Vehicle acceleration, a_R, ranged from -8.25 to +8.25 mph/sec. Steps of 1.0 mph/sec were used from -8.25 mph/sec to -1.25 and from +1.25 to +8.25 mph/sec. Because of the large number of events around cruise (0 mph/sec), the steps from -1.25 to +1.25 mph/sec were taken at 0.5 mph/sec.

Vehicle road power requirement, P_R, in hp, is given by:

$$P_R = P_{R_{\substack{\text{aerodynamic}\\ \text{drag}}}} + P_{R_{\substack{\text{rolling}\\ \text{drag}}}} + P_{R_{\text{acceleration}}}$$

$$= 8.6323 \cdot 10^{-5} \, v_R^{\;3} + 3.6222 \cdot 10^{-4} \, v_R^{\;2} + (.17641 + .52229 \, a_R) v_R$$

This equation is part of the vehicle specification set of Appendix A. In computing road power, P_R, the midpoint of each of the matrix intervals was used.

In applying the matrix values of each component and system performance quantity to a driving mission, the following approach was taken. Over 14.6 hours of actual road velocity-time data on the LA-4 route were analyzed at one-second intervals. The values of v_R and a_R were computed for each one-second event and these were grouped within the matrix step bounds for each midpoint value. The total probability $P_{i,j}$ of each V_R-a_R combination occurring within the 14.6 hours (52,000 seconds) was computed and inserted into the appropriate position of the probability matrix, to serve as the multiplying factor in computing LA-4 mission efficiencies, etc.

Series Hybrid Model

The series system block diagram is shown in Figure F-1.

Step 1. Wheel velocity, w_R, and road torque, τ_R, for a given v_R, a_R and computed value of P_R

$$w_R = \frac{v_R \cdot 44}{\pi r}$$

and

$$\tau_R = \frac{P_R \cdot 1.65 \cdot 10^4}{\pi r \; w_R}$$

Step 2. Motor velocity, w_M, at the output shaft of the traction motor

$$w_M = g_1 \; w_R \cdot Q$$

$$\text{where } g_1 = \frac{w_{M \text{ maximum}}}{v_{R \text{ maximum}}} = \frac{4650 \text{ rpm}}{85 \text{ mph}} \cdot \frac{\pi r}{44} = 3.9$$

Q = gearing factor

= 1 if there is no additional gearing between motor and differential

= numerical values equal to the gear ratios at various road speeds if gear shifting is included

Step 3. Motor torque, τ_M, and motor shaft power, P_{Mo}

In DRIVE ($\tau_R \geq 0$),

$$\tau_M = \frac{\tau_R}{\eta_{g1} \; g1 \; Q}$$

$$P_{Mo} = \frac{P_R \cdot 745.7}{\eta_{g1}}$$

In REGENERATION ($\tau_R < 0$),

$$\tau_M = \frac{\tau_R \; \eta_{g1}}{g_1}$$

$$P_{Mo} = P_R \cdot \eta_{g1} \cdot 745.7$$

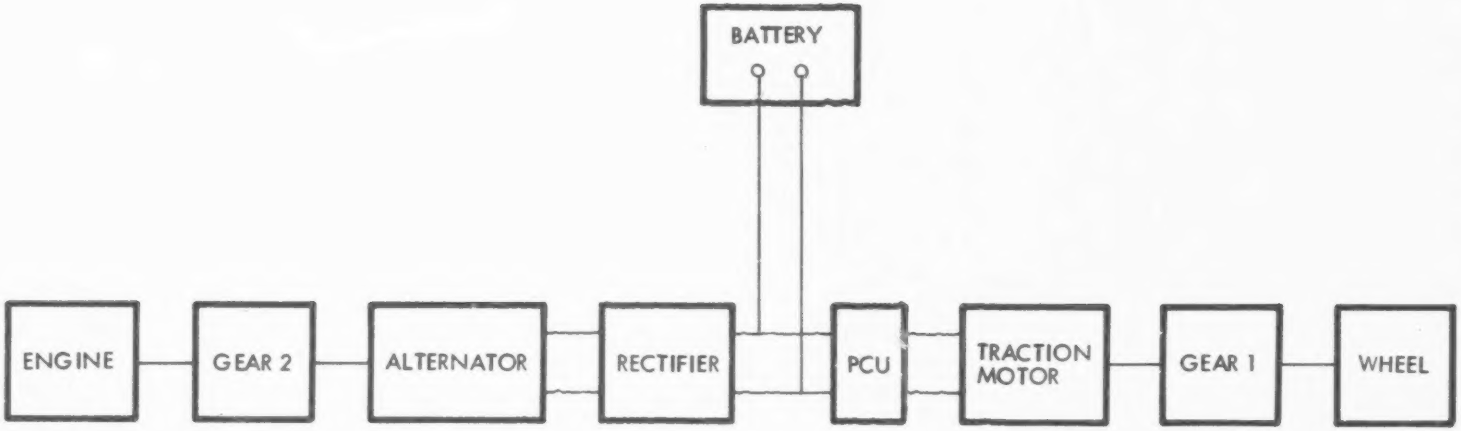
BATTERY
ENGINE
GEAR 2
ALTERNATOR
RECTIFIER
PCU
TRACTION MOTOR
GEAR 1
WHEEL

FIGURE F-1

FULL VOLTAGE SERIES HYBRID POWER TRAIN

The efficiency of the gearing between the motor and the wheels includes the differential and any variable gear step which might be used. In all cases:

$$\eta_{g1} = \eta_{g1(0)} - 0.03 \frac{w_R}{w_{R \text{ at } 85 \text{ mph}}}$$

where $\eta_{g1(0)}$ is assumed to be 0.98 without additional gearing and 0.97 with gearing. Gear train efficiency is taken as a decreasing function of velocity, reflecting the possibility of lubrication losses which would increase with speed, independent of gear tooth loads.

Step 4. Motor current, I_M, is modeled from the characteristic of Figure D-1.

$$I_M = \pm \left(\frac{7}{3} |\tau_M| + 60\right)$$

The plus sign is used for drive conditions of step 3; the negative sign is used for regeneration.

Step 5. Motor efficiency, η_M

Motor efficiency is determined from the characteristics of Figures D-2 & 3. in which η_N is plotted as a function of w_T and motor, I_M. Whenever necessary, the program performs a linear interpolation of the data.

Step 6. Motor terminal electrical power, P_{Mi}, and terminal voltage, v_M

For conditions of drive (step 3)

$$P_{Mi} = \frac{P_{Mo}}{\eta_M}$$

For conditions of regeneration (step 3)

$$P_{Mi} = P_{Mo}\ \eta_M$$

In both cases

$$V_M = \frac{P_{Mi}}{I_M}$$

Step 7. Motor power level for battery-generator combination

The following sets of equations are solved for V_B, α, I_{PCU}, η_{PCU}, and I_G.

In DRIVE:

$$I_{PCU} = \alpha\ I_M$$

$$V_B = V_{Bi} - R_B\ (I_{PCU} - I_G)$$

$$P_{Mi} = \eta_{PCU}\ V_B\ I_{PCU}$$

$$I_G = \frac{P_{IC}\ \eta_S}{V_B}$$

$$\eta_{PCU} = \frac{\alpha V_{Bi} I_M - \alpha R_B - I_M{}^2 - K_1 - K_2 I_M}{\alpha V_{Bi} I_M - \alpha R_B I_M{}^2}$$

In REGENERATION:

$$I_{PCU} = (1-\alpha) I_M$$

$$V_B = V_{Bi} - R_B (I_{PCU} - I_G)$$

$$P_{Mi} = \frac{V_B\ I_{PCU}}{\eta_{PCU}}$$

$$I_G = \frac{P_{IC}\ \eta_S}{V_B}$$

$$\eta_{PCU} = \frac{(1-\alpha)V_{Bi}|I_M|+(1-\alpha)R_B I_M{}^2}{(1-\alpha)V_{Bi}|I_M|+(1-\alpha)R_B I_M{}^2+K_1+K_2|I_M|}$$

The equations for the PCU efficiencies, η_{PCU}, are taken from the development of the PCU efficiencies in Appendix E. In keeping with that work,

$K_1 = 895$, $K_2 = 2.99$ for the 900-amp PCU, which is used in cases without additional gearing

$K_1 = 631$, $K_2 = 3.07$ for the 600-amp PCU, which is used in cases with gearing

V_{Bi} has the value of 240 volts for this and all other models.

In regeneration, if the solution of the equations yields $\alpha > 1$, then α is set to 1, I_{PCU} and η_{PCU} are zero, and the equations are solved for V_B. This corresponds to a situation where the motor acting as a generator and PCU are unable to deliver power to the battery bus.

In drive, elements of the matrix for which the equations yield $\alpha > 1$ are considered invalid elements. These correspond to conditions where the battery voltage falls below motor terminal voltage and no further power can be drawn from the battery.

Several additional computations are required to solve the sets of equations.

$$\eta_S = \eta_{g2}\ \eta_A\ \eta_{RE}$$

η_{g2} is assumed to be a function of vehicle speed only, as the series system generator power (and hence speed) is scheduled according to vehicle speed. The variation of η_{g2} with vehicle speed is shown in Figure F-2.

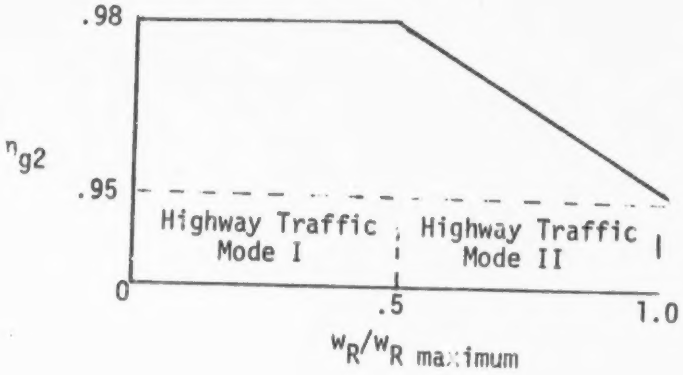

Figure F-2
Gear 2 Efficiency

Alternator efficiency, η_A, is a function of the shaft input power to the alternator, P_{Ai}.

$$P_{Ai} = \eta_{g2} P_{IC}$$

η_A is computed from the alternator characteristics of Figure D-7.

Rectifier efficiency, η_{RE}, is assumed constant at 0.99.

During highway conditions, the engine power is adjusted so that the engine puts out just enough power to propel the car in cruise. The set of drive equations is therefore simplified because $V_B = V_{Bi}$ and $I_{PCU} = I_G$. For highway conditions, the engine power, P_{IC} is determined as follows:

$$I_{PCU} = \alpha I_M$$

$$P_{Mi} = \eta_{PCU} V_B I_{PCU}$$

$$\eta_{PCU} = 1 - \frac{K_1+K_2 I_M}{\alpha V_{Bi} I_M - \alpha R_B I_M^2}$$

These may be solved for η_{PCU}, I_{PCU} and α, when

$$P_{PCU} = \frac{P_{Mi}}{\eta_{PCU}} = P_{RE}$$

$$P_{Ao} = \frac{P_{RE}}{\eta_{RE}}$$

$$P_{Ai} = \frac{P_{Ao}}{\eta_A}$$

$$I_G = I_{PCU} = \frac{V_T\ I_M}{\eta_{PCU}\ V_{Bi}}$$

$$P_{IC} = \frac{I_G\ V_{Bi}}{\eta_S}$$

Step 8. PCU power, P_{PCU}

$$P_{PCU} = \frac{P_{Mi}}{\eta_{PCU}} \text{ in drive}$$

$$P_{PCU} = P_{Mi}\ \eta_{PCU} \text{ in regeneration}$$

Step 9. Power into alternator, P_{Ai}

$$P_{Ai} = \eta_{g2}\ P_{IC}$$

where P_{IC} is an input parameter in urban mode and is evaluated in step 7 for highway mode.

Step 10. Alternator output power, P_{Ao}

$$P_{Ao} = \eta_A\ P_{Ai}$$

Step 11. Alternator power to battery bus, P_{RE}

$$P_{RE} = \eta_{RE}\ P_{Ao}$$

Step 12. Battery power, P_B, and current, I_B

$$P_B = P_{PCU} - P_{RE}$$

$$I_B = \frac{P_B}{V_B}$$

Parallel Hybrid Model

A block diagram of the major elements of the parallel hybrid model is shown in Figure F-3.

Step 1. Wheel velocity, w_R, and road torque, τ_R given v_R, a_R and a computed value of P_R

$$w_R = \frac{VR \cdot 44}{\pi r}$$

$$\tau_R = \frac{P_R \cdot 1.65 \cdot 10^4}{\pi_r \, w_R}$$

Step 2. Engine power, P_{IC}

In urban traffic, $v_R < 42.5$ mph, P_{IC} is an input parameter which is selected (in horsepower) at the start of computation.

In highway traffic, $v_R > 42.5$ mph,

$$P_{IC} = \frac{P_{R[a_R=0]}}{\eta_{g1} \, \eta_{g0}}$$

where $\eta_{g1} = -.03 \left(\frac{w_R}{w_{R\ \text{maximum}}}\right)$

$\eta_{g1(0)}$ is an input parameter of the differential efficiency as in the series system. It is set at 0.97.

η_{g0} is an input parameter, 0.8 or 0.9

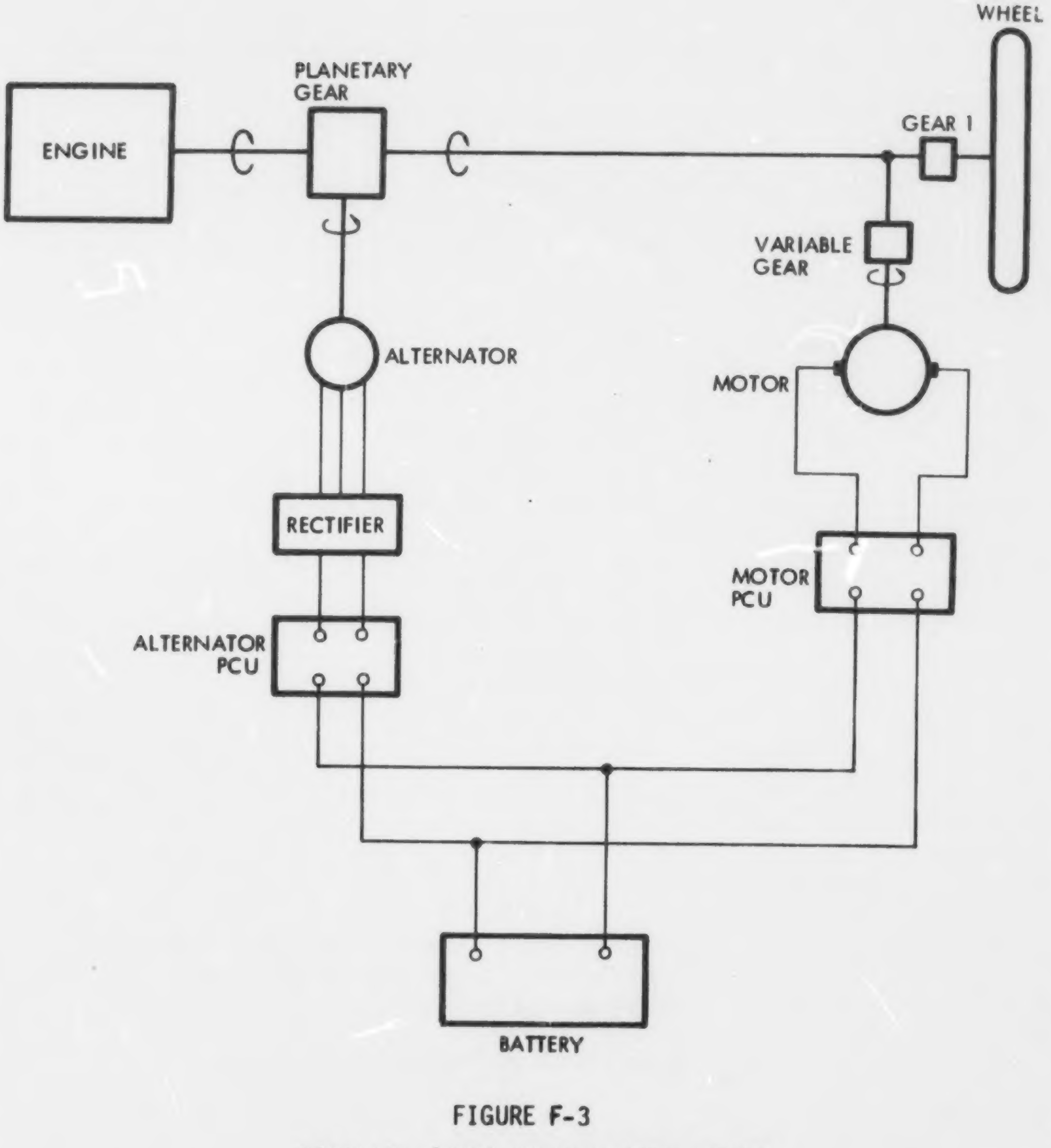
WHEEL
PLANETARY GEAR
ENGINE
GEAR 1
VARIABLE GEAR
ALTERNATOR
MOTOR
RECTIFIER
MOTOR PCU
ALTERNATOR PCU
BATTERY

FIGURE F-3
PARALLEL (EMT) HYBRID POWER TRAIN

Step 3. Power out of planetary gear to wheel, P_0

In urban mode, $P_0 = \eta_{g0} P_{IC} (0.9 \frac{v_R}{42.5})$

In highway mode, $P_0 = \eta_{g0} P_{IC}$

Step 4. Motor shaft power, P_{Mo}

Motor is in drive when $P_R > \eta_{g1} P_0$, and

$$P_{Mo} = \left(\frac{P_R}{\eta_{g1}} - P_0\right) \frac{1}{\eta_{gM}}$$

Motor is in regeneration whenever $P_R < \eta_{g1} P_0$;

if $P_R > 0$, use

$$P_{Mo} = \left(\frac{P_R}{\eta_{g1}} - P_0\right) \eta_{gM}$$

if $P_R < 0$, use

$$P_{Mo} = (\eta_{g1} P_R - P_0)\eta_{gM}$$

The motor speed is $w_M = g_1 w_R \cdot Q$

$$\text{where } g_1 = \frac{w_{M\ \text{maximum}}}{v_{R\ \text{maximum}}} = \frac{7200 \text{ rpm}}{85 \text{ mph}} \cdot \frac{\pi r}{44} = 6.1$$

Q = gearing factor

Q = 1 if there is no additional variable gearing between the motor and differential

Q = numerical values equal to the gear ratios at various road speeds if gear shifting is included.

Step 5. Motor torque, τ_M

$$\tau_M = \frac{P_{Mo} \cdot 1.65 \cdot 10^4}{\pi r\ w_M}$$

Step 6. Motor current, I_M

$|I_M|$ is determined graphically as a function of τ_M from the parallel motor characteristics presented in Figure D-4. I_M is then set positive in drive, negative in regeneration.

Step 7. Motor efficiency, η_M

η_M is determined as a function of w_r and $|I_M|$, from the performance curves of the parallel hybrid motor in Figure D-6.

Step 8. Motor terminal electric power, P_{Mi}, and terminal voltage, v_M

In drive, $P_{Mi} = \dfrac{P_{Mo} \cdot 745.7}{\eta_M}$

In regeneration, $P_{Mi} = \eta_M \cdot P_{Mo} \cdot 745.7$

In both cases, $V_M = \dfrac{P_{Mi}}{I_M}$

Step 9. Power into the alternator, P_{Ai}

In urban mode, $P_{Ai} = (\eta_{g0}\ P_{IC} - P_0) \cdot 745.7$

In highway mode, $P_{Ai} = 0$

Step 10. Alternator system characteristics

η_A is determined from Figure D-8 of Appendix D

$P_{Ao} = \eta_A\ P_{Ai}$

$V_A = 200\ (1-0.9\ \frac{v_R}{42.5})$ for urban operation

$V_A = 0$ in highway mode

$$I_A = \frac{P_{Ao}}{V_A}$$

$\Delta P_{PCUA} = .02\ I_A^2 + 4.13\ I_A + 44.8$ in urban mode

$= 0$ in highway mode

$$P_{PCUA} = P_{Ao} - \Delta P_{PCUA}$$

$$\eta_{PCUA} = \frac{P_{PCUA}}{P_{Ao}}$$

Step 11. Motor power level for battery-generator combination solve the following sets of equations for I_{PCUM}, α, V_B, η_{PCUM}, I_{PCUA}

In drive,

$$I_{PCUM} = \alpha I_M$$

$$V_B = V_{Bi} - R_B(I_{PCUM} - I_{PCUA})$$

$$P_{Mi} = \eta_{PCUM}\ V_B I_{PCUM}$$

$$\eta_{PCUM} = \frac{\alpha V_{Bi} I_M - \alpha R_B\ I_M^2 - K_1 - K_2 I_M}{\alpha V_{Bi} I_M - \alpha R_B I_M^2}$$

$$I_{PCUA} = \frac{P_{PCUA}}{V_B}$$

In regeneration,

$$I_{PCUM} = (1-\alpha) I_M$$

$$V_B = V_{Bi} - R_B(I_{PCUM} - I_{PCUA})$$

$$P_{Mi} = \frac{1}{\eta_{PCUM}} (V_B I_{PCUM})$$

$$\eta_{PCUM} = \frac{(1-\alpha)V_{Bi}|I_M|+(1-\alpha)R_B I_M^2}{(1-\alpha)V_B|I_M|+(1-\alpha)R_B I_M^2+K_1+K_2|I_M|}$$

$$I_{PCUA} = \frac{P_{PCUA}}{V_B}$$

K_1 and K_2 are PCU constants derived in Appendix E.

$K_1 = 895$, $K_2 = 2.99$ for the 900-amp PCU which is used if $Q=1$

$K_1 = 631$, $K_2 = 3.07$ for the 600-amp PCU which is used if Q has values different from 1

In regeneration, if the solution of the equations yields $\alpha > 1$, then α is set to 1, I_{PCUM} and η_{PCUM} are zero, and the equations are solved for V_B and I_{PCUA}. This corresponds to a situation where the motor as a generator and the motor PCU are unable to deliver power to the battery bus.

In drive, elements of the matrix for which the equations yield $\alpha > 1$ are considered invalid elements. These correspond to conditions where the battery voltage falls below motor terminal voltage and no further power can be drawn from the battery.

Step 12. Motor PCU power, P_{PCUM}

$$P_{PCUM} = \frac{P_{Mi}}{\eta_{PCUM}} \text{ in drive}$$

$$P_{PCUM} = P_{Mi}\, \eta_{PCUM} \text{ in regeneration}$$

Step 13. Battery power, P_B, and current, I_B

$$I_B = I_{PCUM} - I_{PCUA}$$

$$P_B = I_B \cdot V_B$$

Computational Procedures for Determining Average and Root Mean Square Performance Values of Power Train Components

Each velocity-acceleration combination (i,j) in the LA-4 matrix has associated with it a probability of occurrence, $P_{i,j}$. The probabilities are used in determining averages and root mean squares of the performance characteristics as follows:

For any characteristic, X, such as motor current or battery power, etc., where the value $X_{i,j}$ is known for the i^{th} velocity, j^{th} acceleration,

$$X_{AVE} = \frac{\Sigma\, X_{i,j}\, P_{i,j}}{\Sigma\, P_{i,j}}$$

$$X_{RMS} = \frac{\Sigma\, (X_{i,j})^2\, P_{i,j}}{\Sigma\, P_{i,j}}$$

Matrix elements in drive for which the equations yield a value of $\alpha > 1$ are excluded from the averages and root mean squares since they are physically unrealizable.

Matrix elements in regeneration for which the equations yield a value of $\alpha > 1$ have α set equal to 1 and are included in the averages. In these cases there is excess regenerative energy which cannot be processed.

Series System Averages and Root Mean Squares

Matrix elements are grouped as follows:

DRIVE: $P_R \geq 0$
REGEN: $P_R < 0$
CHARGE: $I_B < 0$
DISCHARGE: $I_B \geq 0$

The averages for the series system of the quantities P_M, P_{Mi}, P_{PCU}, I_M, and I_{PCU} are averages of the absolute values of those quantities. This procedure was chosen because the rating of the particular component is affected to the first order by the magnitude of the quantity rather than direction of flow.

The average battery loss is the average of $(I_B^2 \cdot R_B)$ for all charge and discharge events.

The average component and subsystem efficiencies are defined as follows:

$$\text{DRIVE } \eta_M = \frac{\text{ave DRIVE } P_{Mo}}{\text{ave DRIVE } P_{Mi}}$$; average motor efficiency only during drive events

$$\text{REGEN } \eta_M = \frac{\text{ave REGEN } P_{Mi}}{\text{ave REGEN } P_{Mo}}$$; average motor efficiency only during regeneration events

$$\text{DRIVE } \eta_{PCU} = \frac{\text{ave DRIVE } P_{Mi}}{\text{ave DRIVE } P_{PCU}}$$; average PCU efficiency only during drive events

$$\text{REGEN } \eta_{PCU} = \frac{\text{ave REGEN } P_{PCU}}{\text{ave REGEN } P_{Mi}}$$; average PCU efficiency only during regeneration events

$$\text{SYSTEM } \eta = \frac{\Sigma\,(\text{DRIVE } P_{R(i,j)} \cdot P_{i,j})}{\text{ave } P_{IC}}$$; $\dfrac{\text{average road positive traction power demand}}{\text{average engine power}}$

$$\eta(\text{ALT}) = \frac{\text{ave } P_{Ao}}{\text{ave } P_{Ai}}$$

Parallel System Averages and Root Mean Squares

Matrix elements are grouped as follows:

DRIVE: $P_R > \eta_{g1} P_0$

REGEN: $P_R \leq \eta_{g1} P_0$

REGEN+: $0 \leq P_R \leq \eta_{g1} P_0$

REGEN-: $P_R < 0$

CHARGE: $I_B < 0$

DISCHARGE: $I_B \geq 0$

The averages for the whole system of P_{Mo}, P_{Mi}, I_M, and I_{PCUM} are averages of the absolute values of those quantities as in the series system.

The average component and subsystem efficiencies are defined in a manner similar to the series system as follows:

$$\text{SYSTEM } \eta = \frac{\Sigma\ (\text{DRIVE } P_{R(i,j)} P_{i,j})}{\text{ave } P_{IC}}$$

$$\text{DRIVE } \eta_M = \frac{\text{ave DRIVE } P_{Mo}}{\text{ave DRIVE } P_{Mi}}$$

$$\text{REGEN } \eta_M = \frac{\text{ave REGEN } P_{Mi}}{\text{ave REGEN } P_{Mo}}$$

$$\text{DRIVE } \eta_{PCUM} = \frac{\text{ave DRIVE } P_{Mi}}{\text{ave DRIVE } P_{PCUM}}$$

$$\text{REGEN } \eta_{PCUM} = \frac{\text{ave REGEN } P_{PCUM}}{\text{ave REGEN } P_{Mi}}$$

$$\eta_{ALT} = \frac{\text{ave } P_{Ao}}{\text{ave } P_{Ai}}$$

$$\eta_{PCUA} = \frac{\text{ave } P_{PCUA}}{\text{ave } P_{Ao}}$$

APPENDIX G

Two sets of computer print out of system and component characteristics are presented.

The first set, corresponding to Run IA, treats a full voltage series hybrid, with a variable gear transmission. The engine power is set at 16 hp in the urban mode and the battery resistance is 0.086Ω. The first sheet presents data which is independent of vehicle acceleration; following sheets show component operating characteristics at the indicated acceleration and speed. Values are computed for the midpoint of the range indicated. Probability refers to the probability of occurrence in the LA-4 data set. Other headings are evident or defined in the nomenclature.

The second set, corresponding to Run TAA presents the data for an EMT with variable gearing. It is using a 0.086Ω battery and a 90% efficient planetary set. The engine power is set at 11.75 hp in the urban mode.

SERIES Run IA
WITH LEARNING
P(IC) = 16 HP
R(B) = .026 OHMS

ANY ACCELERATION

VEHICLE SPEED MPH W_R	PROBABILITY	WHEEL VELOCITY RPM	GEAR 1 EFFICIENCY η_{G1}	MOTOR VELOCITY RPM V_M	ENGINE POWER HP P_{IC}
0.0 TO 5.0	0.14449	3.501+01	0.97911	2.7353+02	1.6 +01
5.0 TO 10.0	0.06105	1.05 +02	0.97735	8.2059+02	1.6 +01
10.0 TO 15.0	0.05550	1.75 +02	0.97558	1.3676+03	1.6 +01
15.0 TO 20.0	0.07735	2.45 +02	0.97382	1.9147+03	1.6 +01
20.0 TO 25.0	0.12642	3.151+02	0.97205	2.4617+03	1.6 +01
25.0 TO 30.0	0.17082	3.851+02	0.97029	3.0088+03	1.6 +01
30.0 TO 35.0	0.14455	4.551+02	0.96852	3.5558+03	1.6 +01
35.0 TO 40.0	0.06595	5.252+02	0.96676	4.1029+03	1.6 +01
40.0 TO 45.0	0.02274	5.952+02	0.96500	3.4875+03	2.7465+01
45.0 TO 50.0	0.01638	6.652+02	0.96323	3.6977+03	3.2325+01
50.0 TO 55.0	0.01858	7.353+02	0.96147	4.3081+03	3.7519+01
55.0 TO 60.0	0.03153	8.053+02	0.95970	3.1455+03	4.3501+01
60.0 TO 65.0	0.01136	8.753+02	0.95794	3.4191+03	5.0229+01
65.0 TO 70.0	0.00220	9.453+02	0.95617	3.6926+03	5.7906+01
70.0 TO 75.0	*0.00000	1.015+03	0.95441	3.9661+03	6.6762+01
75.0 TO 80.0	*0.00000	1.085+03	0.95264	4.2397+03	7.7439+01
80.0 TO 85.0	*0.00000	1.155+03	0.95088	4.5132+03	9.1743+01
85.0 TO 90.0	*0.00000	1.225+03	0.94911	4.7868+03	1.0674+02

VEHICLE SPEED MPH	GEAR 2 EFFICIENCY η_{G2}	GEAR 2 LOSS HP	INPUT POWER KW P_{AI}	ALTERNATOR EFFICIENCY η_A	OUTPUT POWER KW P_{AO}	ALTERNATOR VELOCITY RPM W_A	ALTERNATOR TORQUE FT-LB τ_A
0.0 TO 5.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
5.0 TO 10.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
10.0 TO 15.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
15.0 TO 20.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
20.0 TO 25.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
25.0 TO 30.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
30.0 TO 35.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
35.0 TO 40.0	0.98000	3.2 -01	1.1692+01	.64317	7.5203+00	3.9996+03	2.059 +01
40.0 TO 45.0	0.98000	5.4931-01	2.0071+01	.73077	1.4667+01	3.9996+03	3.5345+01
45.0 TO 50.0	0.97647	7.6061-01	2.3538+01	.75857	1.7855+01	4.9407+03	3.3554+01
50.0 TO 55.0	0.97294	1.0152+00	2.7221+01	.78872	2.1469+01	5.8818+03	3.2596+01
55.0 TO 60.0	0.96941	1.3306+00	3.1446+01	.82005	2.5788+01	6.8228+03	3.2462+01
60.0 TO 65.0	0.96588	1.7137+00	3.6178+01	.85256	3.0844+01	7.7639+03	3.2819+01
65.0 TO 70.0	0.96235	2.18 +00	4.1555+01	.88165	3.6637+01	8.705 +03	3.3622+01
70.0 TO 75.0	0.95882	2.749 +00	4.7734+01	.90399	4.3151+01	9.6461+03	3.4853+01
75.0 TO 80.0	0.95529	3.462 +00	5.5164+01	.91356	5.0396+01	1.0587+04	3.6698+01
80.0 TO 85.0	0.95176	4.4253+00	6.5113+01	.90150	5.8699+01	1.1528+04	3.9781+01
85.0 TO 90.0	0.94823	5.5256+00	7.5477+01	.90150	6.8043+01	1.2469+04	4.2632+01

SERIES Run IA
WITH GEARING
P(IC) = 16 HP
R(B) = .086 CHMS

ACCELERATICN = -6.25 TC -7.25 MPH/SEC

PROBABILITY = 0.0CC77

VEHICLE SPEED MPH	PROBABILITY P_{ij}	POWER DEMAND HP P_R	GEAR LOSS HP	TORQUE AT WHEEL FT-LB T_R	MOTOR TORQUE FT-LB τ_M	MOTOR POWER HP P_{MO}	POWER INPUT KW P_{MI}	MOTOR EFFICIENCY η_M	MOTOR LOSS KW ΔP_M	MOTOR CURRENT AMPS I_M	TERMINAL VOLTAGE V_M
0.0 TO 5.0	0.00CC4	-9.674+00	2.9878-01	-1.4512+03	-1.8003+02	-9.375+00	-2.7909+00	0.39518	4.2CC7+00	-4.8006+02	5.8136+00
5.0 TO 10.0	0.0C014	-2.897+01	9.4607-01	-1.4489+03	-1.7941+02	-2.803+01	-1.4718+01	0.70409	6.1854+00	-4.7863+02	3.075 +01
10.0 TO 15.0	0.00029	-4.816+01	1.6575+00	-1.4449+03	-1.766 +02	-4.65 +01	-2.724 +01	0.78543	7.4415+00	-4.7674+02	5.7138+01
15.0 TO 20.0	C.00C16	-6.717+01	2.4301+00	-1.4394+03	-1.7759+02	-6.474+01	-4.0044+01	0.82541	8.2356+00	-4.7439+02	8.4413+01
20.0 TO 25.0	0.00010	-8.593+01	3.2606+00	-1.4323+03	-1.7639+02	-8.267+01	-5.2898+01	0.85800	8.7547+00	-4.7157+02	1.1217+02
25.0 TO 30.0	C.CCC04	-1.043+02	4.145 +00	-1.4235+03	-1.7498+02	-1.002+02	-6.5601+01	0.87755	9.1535+00	-4.683 +02	1.4008+02
30.C TO 35.0	*00.00000	-1.224+02	5.079 +00	-1.4131+03	-1.7339+02	-1.173+02	-7.8042+01	0.89150	9.4978+00	-4.6458+02	1.6798+02
35.0 TO 40.0	*00.CC000	-1.401+02	6.0579+00	-1.4011+03	-1.716 +02	-1.34 +02	-8.998 +01	0.90012	9.9843+00	-4.604 +02	1.9544+02
40.0 TO 45.C	*C0.00000	-1.572+02	7.0763+00	-1.3875+03	-2.2616+02	-1.501+02	-9.8102+01	0.87603	1.3882+01	-5.877 +02	1.6692+02
45.0 TO 50.0	*0C.CC000	-1.738+02	8.1287+00	-1.3722+03	-2.2326+02	-1.656+02	-1.0936+02	C.88515	1.415 +01	-5.8094+02	1.8825+02
50.0 TO 55.0	*0C.C0000	-1.897+02	9.2088+00	-1.3554+03	-2.201 +02	-1.805+02	-1.2015+02	0.89247	1.4476+01	-5.7358+02	2.0948+02
55.0 TO 60.0	*00.CCC00	-2.049+02	1.031 +01	-1.3369+03	-3.2506+02	-1.946+02	-1.2168+02	0.83816	2.3494+01	-8.1846+02	1.4867+02
60.0 TO 65.0	*00.00000	-2.194+02	1.1425+01	-1.3168+03	-3.1558+02	-2.08 +02	-1.3171+02	0.84899	2.3427+01	-8.0566+02	1.6348+02
65.0 TO 70.0	*0C.C0000	-2.331+02	1.2547+01	-1.295 +03	-3.1372+02	-2.205+02	-1.4113+02	0.85810	2.3339+C1	-7.92 +02	1.782 +02

VEHICLE SPEED MPH	ALPHA α	PCU POWER KW P_{PCU}	PCU EFFICIENCY η_{PCU}	PCU LOSS KW ΔP_{PCU}	PCU INPUT CURRENT AMPS I_{PCU}	BATTERY POWER KW P_B	BATTERY VOLTAGE V_B	BATTERY CURRENT AMPS I_B	BATTERY LOSS KW ΔP_B	RECTIFIER CURRENT AMPS I_A
0.0 TO 5.0	C.59166	-5.7276-01	0.34854	1.8181+00	-4.0034+00	-8.4177+00	2.4258+02	-3.4643+01	1.C321-01	3.0489+01
5.0 TO 10.0	C.89114	-1.2872+01	0.87460	1.8456+00	-5.2102+01	-2.0317+01	2.4706+02	-8.2236+01	5.816 -01	2.9985+01
10.0 TO 15.0	C.78819	-2.5367+01	0.93125	1.8726+00	-1.0097+02	-3.2812+01	2.5122+02	-1.3061+02	1.467 +00	2.9488+01
15.0 TO 20.0	0.685C8	-3.8146+01	0.95259	1.8981+00	-1.4939+02	-4.5591+01	2.5534+02	-1.7854+02	2.7416+00	2.9012+01
20.0 TO 25.0	C.58321	-5.0976+01	0.96367	1.9217+00	-1.9654+02	-5.8421+01	2.5936+02	-2.2525+02	4.3634+00	2.8563+01
25.0 TO 30.0	0.48357	-6.3658+01	0.97036	1.9428+00	-2.4184+02	-7.1103+01	2.6322+02	-2.7C13+02	6.2753+00	2.8144+01
30.0 TO 35.0	C.38643	-7.6C81+01	0.97486	1.9613+00	-2.8505+02	-8.3526+01	2.669 +02	-3.1294+02	8.4222+00	2.7756+01
35.0 TO 40.0	0.29297	-8.8004+01	0.97803	1.9768+00	-3.2551+02	-9.5449+01	2.7035+02	-3.5305+02	1.0719+01	2.7402+01
40.0 TO 45.0	0.40629	-9.5801+01	0.97654	2.3013+00	-3.4892+02	-1.1035+02	2.7456+02	-4.0193+02	1.3093+01	5.295 +01
45.0 TO 50.0	0.33839	-1.0704+02	0.97879	2.3192+00	-3.8435+02	-1.2472+02	2.7851+02	-4.4784+02	1.7248+01	6.3479+01
50.0 TO 55.0	0.27251	-1.1782+02	C.98057	2.3343+00	-4.1727+02	-1.3909+02	2.8236+02	-4.9261+02	2.0869+01	7.5297+01
55.0 TO 60.0	C.48842	-1.188 +02	0.97638	2.8738+00	-4.187 +02	-1.4434+02	2.8375+02	-5.0871+02	2.2255+01	9.0001+01
60.0 TO 65.0	0.44412	-1.2882+02	0.97808	2.8871+00	-4.4785+02	-1.5939+02	2.8765+02	-5.5411+02	2.6405+01	1.0619+02
65.0 TO 70.0	0.40119	-1.3824+02	0.97947	2.8971+00	-4.7426+02	-1.7456+02	2.9149+02	-5.9887+02	3.0843+01	1.2448+02

```
SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATICN = -7.25 TC -6.25 MPH/SEC

PROBABILITY =  C.C0146

   VEHICLE    PROBABILITY  POWER       GEAR        TURQUE       MOTOR      MOTOR      POWER      MOTOR       MCTOR      MOTOR      TERMINAL
    SPEED                  DEMAND      LUSS       AT WHEEL     TURQUE      POWER      INPLT    EFFICIENCY    LCSS      CURRENT     VOLTAGE
     MPH                    HP          HP         FT-LB        FT-LB       HP         KW                    KW         AMPS         V

  0.0 TO  5.0   C.COCC6 -8.369+00  2.5845-01 -1.2553+03 -1.5573+02 -8.11  +00 -2.2311+00   0.36890  3.8168+00 -4.2337+02  5.2699+00
  5.0 TO 10.C   C.COC35 -2.506+01  8.1819-01 -1.253 +03 -1.5516+02 -2.424+01 -1.3062+01   0.72257  5.0152+00 -4.2205+02  3.095 +01
 10.0 TO 15.0   0.C0040 -4.163+01  1.4328+00 -1.2491+03 -1.5439+02 -4.02  +01 -2.3941+01   0.79855  6.0356+00 -4.2026+02  5.6968+01
 15.0 TO 20.0   C.00029 -5.803+01  2.0995+00 -1.2436+03 -1.5343+02 -5.593+01 -3.4933+01   0.83750  6.7777+00 -4.18  +02  8.3571+01
 20.0 TO 25.0   C.COC16 -7.418+01  2.8147+00 -1.2364+03 -1.5227+02 -7.137+01 -4.6093+01   0.86604  7.1292+00 -4.1529+02  1.1098+02
 25.0 TO 30.0   C.CC010 -9.002+01  3.5747+00 -1.2276+03 -1.5091+02 -8.645+01 -5.7006+01   0.88424  7.4628+00 -4.1213+02  1.3832+02
 30.0 TO 35.0   0.CCC10 -1.054+02  4.3751+00 -1.2172+03 -1.4936+02 -1.011+02 -6.7645+01   0.89706  7.7621+00 -4.085 +02  1.6599+02
 35.0 TO 40.0 *C0.00000 -1.205+02  5.2111+00 -1.2052+03 -1.4761+02 -1.153+02 -7.7768+01   0.90437  8.2233+00 -4.0443+02  1.9229+02
 40.0 TO 45.0 *0C.00000 -1.35  +02  6.0774+00 -1.1916+03 -1.9423+02 -1.289+02 -8.5207+01   0.88593  1.057  +01 -5.1321+02  1.6602+02
 45.0 TO 50.0 *0C.CCCC0 -1.49  +02  6.9685+00 -1.1764+03 -1.9139+02 -1.42  +02 -9.4716+01   0.89421  1.1205+01 -5.0658+02  1.8696+02
 50.0 TO 55.0 *00.CC00C -1.623+02  7.8781+00 -1.1595+03 -1.883 +02 -1.544+02 -1.0357+02   0.89921  1.1608+01 -4.9937+02  2.074 +02
 55.0 TO 60.0 *0C.CC000 -1.749+02  8.7996+00 -1.141  +03 -2.7744+02 -1.661+02 -1.0574+02   0.85340  1.8164+01 -7.0734+02  1.4949+02
 60.0 TO 65.0 *00.00000 -1.868+02  9.7259+00 -1.1209+03 -2.7204+02 -1.77  +02 -1.1393+02   0.86273  1.8127+01 -6.9476+02  1.6399+02
 65.0 TO 7C.0 *CC.CC000 -1.978+02  1.0649+01 -1.0992+03 -2.6627+02 -1.872+02 -1.2159+02   0.87101  1.8C06+01 -6.813 +02  1.7847+02

   VEHICLE       ALPHA     PCU        PCU          PCU      PCU INPUT    BATTERY     BATTERY    BATTERY     BATTERY    RECTIFIER
    SPEED                 POWER    EFFICIENCY      LOSS      CURRENT      POWER      VOLTAGE    CURRENT      LOSS       CURRENT
     MPH                   KW                       KW        AMPS         KW           V         AMPS        KW          AMPS

  0.0 TO  5.0   C.99479 -5.3497-01   0.23977  1.6961+00 -2.2031+00 -7.9799+00  2.4282+02 -3.2862+01  9.2877-02  3.0500+01
  5.0 TO 10.0   C.85098 -1.1343+01   0.86838  1.7192+00 -4.6007+01 -1.8788+01  2.4655+02 -7.6204+01  4.9961-01  3.0047+01
 10.0 TO 15.0   C.78884 -2.22  +01   0.92729  1.74C5+00 -8.8737+01 -2.9645+01  2.5018+02 -1.1849+02  1.2075+00  2.9611+01
 15.0 TO 20.0   C.68725 -3.3172+01   0.94961  1.7603+00 -1.3072+02 -4.0617+01  2.5375+02 -1.6006+02  2.2084+00  2.9196+01
 20.0 TO 25.0   C.58527 -4.4314+01   0.96141  1.7785+00 -1.7223+02 -5.1759+01  2.5729+02 -2.0116+02  3.4803+00  2.8793+01
 25.0 TO 30.0   0.48604 -5.5212+01   0.96852  1.7944+00 -2.1181+02 -6.2657+01  2.6066+02 -2.4037+02  4.989  +00  2.842  +01
 30.0 TO 35.0   0.38923 -6.5837+01   0.97327  1.808  +00 -2.495  +02 -7.3282+01  2.6388+02 -2.7771+02  6.6327+00  2.8074+01
 35.0 TO 40.0   0.29630 -7.5949+01   0.97661  1.8186+00 -2.846  +02 -8.3394+01  2.6687+02 -3.125  +02  8.3981+00  2.776  +01
 40.0 TO 45.0   0.40245 -8.3102+01   0.97530  2.1044+00 -3.0666+02 -9.7657+01  2.7099+02 -3.6037+02  1.1760+01  5.3649+01
 45.0 TO 50.0   0.33420 -9.2599+01   0.97765  2.1166+00 -3.3728+02 -1.1028+02  2.7455+02 -4.0169+02  1.3876+01  6.4396+01
 50.0 TO 55.0   C.26916 -1.0144+02   0.97947  2.1259+00 -3.6495+02 -1.2271+02  2.7797+02 -4.4148+02  1.6762+01  7.6488+01
 55.0 TO 60.0   0.47547 -1.0313+02   0.97536  2.6046+00 -3.689  +02 -1.2867+02  2.7958+02 -4.6025+02  1.8217+01  9.1343+01
 60.0 TO 65.0   C.43399 -1.1132+02   0.97708  2.6103+00 -3.9324+02 -1.4189+02  2.831  +02 -5.0121+02  2.1684+01  1.079  +02
 65.0 TO 70.0   C.39062 -1.1878+02   0.97851  2.6131+00 -4.1517+02 -1.553  +02  2.8659+02 -5.4191+02  2.5235+01  1.266  +02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATICN = -6.25 TO -5.25 MPH/SEC

PROBABILITY =  0.00392

   VEHICLE    PROBABILITY  POWER       GEAR      TORQUE      MOTOR      MOTOR       POWER       MOTOR        MCTOR      MOTOR      TERMINAL
    SPEED                  DEMAND      LOSS     AT WHEEL     TORQUE     POWER       INPUT     EFFICIFNCY     LCSS      CURRENT     VOLTAGE
     MPH                    HP          HP        FT-LB      FT-LB       HP          KW                       KW        AMPS          V

  0.0 TO  5.0   C.00C27 -7.063+00  2.1813-01 -1.0594+C3 -1.3143+02 -6.845+00 -1.8039+00    0.35341   3.3CC4+00 -3.6668+02  4.9198+00
  5.0 TO 10.0   0.0C099 -2.114+01  6.903 -01 -1.0571+C3 -1.3091+02 -2.045+01 -1.1365+C1    0.74514   3.887 +00 -3.6546+02  3.1098+01
 10.0 TO 15.0   0.00110 -3.51 +01  1.2081+00 -1.0532+C3 -1.3018+02 -3.39 +01 -2.0541+01    0.81257   4.7382+00 -3.6377+02  5.6469+01
 15.0 TO 20.0   0.00C78 -4.889+01  1.7688+00 -1.0477+03 -1.2926+02 -4.712+01 -2.9741+01    0.84631   5.4CC7+00 -3.6162+02  8.2243+01
 20.0 TO 25.0   0.00050 -6.243+01  2.3689+00 -1.0405+C3 -1.2815+02 -6.006+01 -3.9156+01    0.87419   5.6348+00 -3.5901+02  1.0906+02
 25.0 TO 30.0   C.00022 -7.566+01  3.0044+00 -1.0318+03 -1.2683+02 -7.266+01 -4.8279+01    0.89101   5.9C51+00 -3.5595+02  1.3563+02
 30.0 TO 35.0   C.00002 -8.852+01  3.6711+00 -1.0214+03 -1.2532+02 -8.485+01 -5.7046+01    0.90157   6.228 +00 -3.5243+02  1.6186+02
 35.0 TO 40.0   C.000C4 -1.009+02  4.3642+00 -1.0C94+03 -1.2362+02 -9.657+01 -6.5371+01    0.90770   6.6466+00 -3.4846+02  1.876 +02
 40.0 TO 45.0 *00.00000 -1.128+02  5.0786+00 -9.9579+C2 -1.6231+02 -1.077+02 -7.1742+01    0.89265   8.6273+00 -4.3872+02  1.6352+02
 45.0 TO 50.C *CC.CC000 -1.242+02  5.8083+00 -9.8C54+02 -1.5953+02 -1.183+02 -7.9362+01    0.89892   8.9237+00 -4.3223+02  1.8361+02
 50.0 TO 55.0 *00.00000 -1.349+02  6.5473+00 -9.6368+C2 -1.5649+02 -1.283+02 -8.6687+01    0.90559   9.0367+00 -4.2515+02  2.0389+02
 55.0 TO 60.0 *C0.00000 -1.449+02  7.2892+00 -9.452 +02 -2.2981+02 -1.376+02 -8.8892+01    C.86607   1.3746+01 -5.9623+02  1.4909+02
 60.0 TO 65.0 *00.00000 -1.541+02  8.0266+00 -9.2509+02 -2.245 +02 -1.461+02 -9.5355+01    0.87491   1.3633+01 -5.8385+02  1.6332+02
 65.0 TO 70.0 *0C.C0000 -1.626+02  8.7521+00 -9.0337+02 -2.1883+02 -1.538+02 -1.0129+02    C.88291   1.3433+01 -5.706 +02  1.7752+02

   VEHICLE      ALPHA     PCU         PCU         PCU     PCU INPUT   BATTERY     BATTERY     BATTERY     BATTERY   RECTIFIER
    SPEED                 POWER    EFFICIENCY     LOSS     CURRENT     POWER      VOLTAGE     CURRENT      LOSS      CURRENT
     MPH                   KW                      KW       AMPS        KW           V         AMPS         KW        AMPS

  0.0 TO  5.0   C.99737 -2.3333-01   0.12934   1.5706+00 -9.6112-01 -7.6783+00  2.4277+02 -3.1627+01  8.6025-02  3.0515+01
  5.0 TO 10.0   C.85126 -9.7763+C0   0.86020   1.5887+00 -3.9739+01 -1.7221+01  2.4601+02 -7.0002+01  4.2142-01  3.0113+01
 10.0 TO 15.0   0.79101 -1.8936+01   0.92187   1.6048+00 -7.6021+01 -2.6381+01  2.491 +02 -1.059 +02  9.6462-01  2.974 +01
 15.0 TO 20.0   0.69155 -2.8121+01   0.94555   1.6192+00 -1.1154+02 -3.5566+01  2.5212+02 -1.4106+02  1.7114+00  2.9383+01
 20.0 TO 25.0   C.59035 -3.7524+01   0.95830   1.6325+00 -1.4706+02 -4.4969+01  2.5514+02 -1.7624+02  2.6714+00  2.9035+01
 25.0 TO 30.0   0.49221 -4.6635+01   0.96595   1.6435+00 -1.8074+02 -5.408 +01  2.5802+02 -2.096 +02  3.7781+00  2.8712+01
 30.0 TO 35.0   0.39713 -5.5394+01   0.97103   1.6521+00 -2.1246+02 -6.2839+01  2.6072+02 -2.4102+02  4.5558+00  2.8414+01
 35.0 TO 40.0   0.30541 -6.3712+01   0.97463   1.6583+00 -2.4203+02 -7.1157+01  2.6324+02 -2.7032+02  6.2841+00  2.8142+01
 40.0 TO 45.0   0.40415 -6.9839+01   0.97348   1.9026+00 -2.6141+02 -8.4394+01  2.6716+02 -3.1589+02  8.5816+00  5.4417+01
 45.0 TO 50.0   0.33699 -7.7453+01   0.97594   1.9C92+00 -2.8657+02 -9.5136+01  2.7027+02 -3.52  +02  1.0655+01  6.5414+01
 50.0 TO 55.0   0.27058 -8.4773+01   0.97792   1.9138+00 -3.1011+02 -1.0604+02  2.7336+02 -3.8793+02  1.2942+01  7.7776+01
 55.0 TO 60.0   0.47213 -8.6568+01   0.97385   2.3243+00 -3.1473+02 -1.121 +02  2.7506+02 -4.0759+02  1.4286+01  9.2847+01
 60.0 TO 65.0   0.42724 -9.3032+01   0.97563   2.3231+00 -3.344 +02 -1.2359+02  2.7821+02 -4.4427+02  1.6974+01  1.098 +02
 65.0 TO 70.0   0.38346 -9.8977+01   0.97710   2.319 +00 -3.518 +02 -1.353 +02  2.8135+02 -4.809 +02  1.9889+01  1.2896+02
```

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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATION = -5.25 TO -4.25 MPH/SEC                                                                                    5

PROBABILITY =  0.01159

  VEHICLE    PROBABILITY  POWER      GEAR      TORQUE      MOTOR       MOTOR       POWER        MOTOR        MOTOR      MOTOR      TERMINAL
   SPEED                  DEMAND     LOSS     AT WHEEL     TORQUE      POWER       INPUT     EFFICIENCY      LOSS      CURRENT     VOLTAGE
    MPH                     HP        HP        FT-LB       FT-LB        HP          KW                        KW        AMPS          V

 0.0 TO  5.0   0.00083 -5.757+00  1.7781-01 -8.6363+02 -1.0713+02 -5.579+00 -1.526 +00    0.36677  2.6347+00 -3.0999+02  4.923 +00
 5.0 TO 10.0   0.00227 -1.722+01  5.6242-01 -8.6133+02 -1.0665+02 -1.666+01 -9.4327+00    0.75908  2.9537+00 -3.0887+02  3.054 +01
10.0 TO 15.0   0.00357 -2.858+01  9.8353-01 -8.5742+02 -1.0597+02 -2.759+01 -1.6984+01    0.82534  3.5542+00 -3.0728+02  5.5274+01
15.0 TO 20.0   0.00249 -3.975+01  1.4382+00 -8.5168+02 -1.051 +02 -3.831+01 -2.4557+01    0.85948  4.0148+00 -3.0524+02  8.0454+01
20.0 TO 25.0   0.00145 -5.068+01  1.923 +00 -8.4473+02 -1.0402+02 -4.876+01 -3.1984+01    0.87964  4.3762+00 -3.0273+02  1.0565+02
25.0 TO 30.0   0.00062 -6.13 +01  2.4341+00 -8.3596+02 -1.0276+02 -5.886+01 -3.9248+01    0.89405  4.6508+00 -2.9977+02  1.3092+02
30.0 TO 35.0   0.00024 -7.154+01  2.9672+00 -8.2557+02 -1.0129+02 -6.858+01 -4.6221+01    0.90380  4.9158+00 -2.9636+02  1.5596+02
35.0 TO 40.0   0.00008 -8.135+01  3.5174+00 -8.1356+02 -9.9639+01 -7.783+01 -5.2806+01    0.90976  5.2375+00 -2.9249+02  1.8054+02
40.0 TO 45.0 *00.00000 -9.065+01  4.0796+00 -7.9993+02 -1.3038+02 -8.657+01 -5.8109+01    0.90005  6.453 +00 -3.6423+02  1.5953+02
45.0 TO 50.0 *00.00000 -9.939+01  4.6481+00 -7.8469+02 -1.2766+02 -9.474+01 -6.3953+01    0.90519  6.6579+00 -3.5788+02  1.787 +02
50.0 TO 55.0   0.00002 -1.074+02  5.2167+00 -7.6782+02 -1.2469+02 -1.022+02 -6.9343+01    0.90920  6.9251+00 -3.5094+02  1.9759+02
55.0 TO 60.0   0.00002 -1.148+02  5.7787+00 -7.4934+02 -1.8219+02 -1.091+02 -7.1619+01    0.88015  9.7515+00 -4.8511+02  1.4763+02
60.0 TO 65.0 *00.00000 -1.215+02  6.3273+00 -7.2924+02 -1.7697+02 -1.152+02 -7.6281+01    0.88789  9.6317+00 -4.7294+02  1.6129+02
65.0 TO 70.0 *00.00000 -1.273+02  6.8546+00 -7.0751+02 -1.7138+02 -1.204+02 -8.0309+01    0.89376  9.546 +00 -4.599 +02  1.7462+02

  VEHICLE       ALPHA       PCU        PCU          PCU     PCU INPUT    BATTERY     BATTERY     BATTERY     BATTERY   RECTIFIER
   SPEED                   POWER    EFFICIENCY      LOSS     CURRENT      POWER      VOLTAGE     CURRENT      LOSS      CURRENT
    MPH                     KW                       KW       AMPS          KW          V          AMPS         KW        AMPS

 0.0 TO  5.0   0.55886 -8.5698-02    0.05615  1.4403+00 -3.5312-01 -7.5307+00  2.4268+02 -3.103 +01  8.281 -02  3.0526+01
 5.0 TO 10.0   0.69473 -7.9789+00    0.84587  1.4538+00 -3.2513+01 -1.5423+01  2.454 +02 -6.2852+01  3.3973-01  3.0188+01
10.0 TO 15.0   0.79630 -1.5519+01    0.91373  1.4651+00 -6.259 +01 -2.2964+01  2.4795+02 -9.2616+01  7.3769-01  2.9877+01
15.0 TO 20.0   0.65808 -2.3082+01    0.93993  1.4751+00 -9.2154+01 -3.0527+01  2.5047+02 -1.2187+02  1.2774+00  2.9576+01
20.0 TO 25.0   0.60160 -3.0501+01    0.95362  1.4833+00 -1.206 +02 -3.7946+01  2.5289+02 -1.5004+02  1.9362+00  2.9293+01
25.0 TO 30.0   0.50647 -3.7758+01    0.96204  1.4896+00 -1.4794+02 -4.5203+01  2.5522+02 -1.7711+02  2.6977+00  2.9026+01
30.0 TO 35.0   0.41370 -4.4727+01    0.96767  1.4939+00 -1.7375+02 -5.2172+01  2.5742+02 -2.0267+02  3.5325+00  2.8778+01
35.0 TO 40.0   0.32390 -5.131 +01    0.97166  1.4961+00 -1.9775+02 -5.8755+01  2.5947+02 -2.2644+02  4.4098+00  2.8551+01
40.0 TO 45.0   0.41152 -5.6412+01    0.97080  1.6967+00 -2.1434+02 -7.0967+01  2.6319+02 -2.6964+02  6.2528+00  5.5239+01
45.0 TO 50.0   0.34568 -6.2255+01    0.97344  1.6982+00 -2.3416+02 -7.9938+01  2.6586+02 -3.0068+02  7.7751+00  6.65  +01
50.0 TO 55.0   0.28205 -6.7646+01    0.97551  1.6976+00 -2.5195+02 -8.8918+01  2.6848+02 -3.3119+02  9.4329+00  7.919 +01
55.0 TO 60.0   0.46927 -6.9584+01    0.97159  2.0341+00 -2.5746+02 -9.5125+01  2.7027+02 -3.5196+02  1.0653+01  9.449 +01
60.0 TO 65.0   0.42491 -7.4255+01    0.97343  2.0261+00 -2.7198+02 -1.0482+02  2.7302+02 -3.8394+02  1.2677+01  1.1189+02
65.0 TO 70.0   0.38259 -7.8294+01    0.97491  2.015 +00 -2.8394+02 -1.1461+02  2.7574+02 -4.1568+02  1.4859+01  1.3159+02
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```
SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .C86 CHMS

ACCELERATION = -4.25 TO -3.25 MPH/SEC
                                                                                                                    6
PROBABILITY =  0.02551

   VEHICLE    PROBABILITY  POWER      GEAR       TORQUE       MOTOR      MOTOR      POWER       MOTOR       MOTOR     MOTOR       TERMINAL
    SPEED                  DEMAND     LOSS      AT WHEEL      TORQUE     POWER      INPUT     EFFICIENCY    LOSS      CURRENT     VOLTAGE
     MPH                     HP        HP        FT-LB        FT-LB       HP         KW                     KW        AMPS          V

  0.0 TO  5.0   0.00263 -4.451+00  1.3748-01 -6.6777+02 -8.284 +01 -4.314+00 -1.2539+00  0.38976  1.9632+00 -2.5329+02  4.9505+00
  5.0 TO 10.0   0.00455 -1.33 +01  4.3452-01 -6.6548+02 -8.2405+01 -1.287+01 -7.4962+00  0.78078  2.1C46+00 -2.5227+02  2.9714+01
 10.0 TU 15.0   C.CC555 -2.205+01  7.5888-01 -6.6156+02 -8.1771+01 -2.129+01 -1.3343+01  0.84039  2.5343+C0 -2.5079+02  5.3206+01
 15.0 TO 20.0   0.CC565 -3.061+01  1.1075+00 -6.5602+02 -8.0938+01 -2.95 +01 -1.9144+01  C.87004  2.8553+00 -2.4885+02  7.6928+01
 20.C TO 25.0   0.C0421 -3.893+01  1.4771+00 -6.4887+02 -7.9909+01 -3.745+01 -2.4768+01  0.88680  3.1616+00 -2.4645+02  1.005 +02
 25.C TO 30.0   0.00189 -4.694+01  1.8638+00 -6.401 +02 -7.8684+01 -4.507+01 -3.0147+01  0.89687  3.4664+00 -2.4359+02  1.2375+02
 30.0 TO 35.0   C.C0065 -5.457+01  2.2632+00 -6.2971+02 -7.7265+01 -5.231+01 -3.5316+01  0.90534  3.6524+00 -2.4028+02  1.4697+02
 35.0 TO 40.0   0.00014 -6.177+01  2.6706+00 -6.177 +02 -7.5652+01 -5.909+01 -4.0108+01  0.91009  3.9621+00 -2.3651+02  1.6957+02
 40.0 TO 45.0 *0C.C0000 -6.846+01  3.0808+00 -6.0437+02 -9.8462+01 -6.538+01 -4.4047+01  0.90346  4.7C66+00 -2.8974+02  1.5202+02
 45.0 TO 50.0 *00.C00C0 -7.458+01  3.4879+00 -5.8883+02 -9.5799+01 -7.109+01 -4.8106+01  0.90736  4.91C3+00 -2.8353+02  1.6967+02
 50.0 TO 55.0 *00.CCC00 -8.007+01  3.886 +00 -5.7196+02 -9.2893+01 -7.618+01 -5.1766+01  0.91115  5.0474+00 -2.7673+02  1.8706+02
 55.0 TO 60.0   0.00002 -8.486+01  4.2683+00 -5.5348+02 -1.3457+02 -8.059+01 -5.3729+01  0.89397  6.3725+00 -3.74  +02  1.4366+02
 60.0 TO 65.0   C.00C02 -8.889+01  4.6278+00 -5.3338+02 -1.2944+02 -8.426+01 -5.6496+01  0.89907  6.342 +00 -3.6203+02  1.5605+02
 65.0 TO 70.0 *00.00000 -9.209+01  4.957 +00 -5.1166+02 -1.2394+02 -8.714+01 -5.8696+01  0.90328  6.2848+00 -3.4919+02  1.6809+02

   VEHICLE      ALPHA      PCU        PCU         PCU      PCU INPUT   BATTERY    BATTERY    BATTERY     BATTERY    RECTIFIER
    SPEED                 POWER    EFFICIENCY     LOSS      CURRENT     POWER     VOLTAGE    CURRENT      LOSS       CURRENT
     MPH                   KW                     KW         AMPS        KW          V         AMPS        KW          AMPS

  0.0 TO  5.0   1.00000  0.     +00  0.00000  1.2539+00  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.0967-02  3.0533+01
  5.0 TO 10.0   C.89590 -6.1815+00  0.82461  1.3147+00 -2.5252+01 -1.3626+01  2.4479+02 -5.5665+01  2.6848-01  3.0263+01
 10.0 TO 15.0   0.80574 -1.2022+01  C.90095  1.3217+00 -4.8717+01 -1.9467+01  2.4677+02 -7.8887+01  5.3519-01  3.002 +01
 15.0 TO 20.0   0.71215 -1.7816+01  0.93066  1.3273+00 -7.163 +01 -2.5261+01  2.4872+02 -1.0156+02  8.8709-01  2.9784+01
 20.0 TO 25.0   C.62049 -2.3437+C1  0.94625  1.3312+00 -9.353 +01 -3.0882+01  2.5058+02 -1.2324+02  1.3061+00  2.9563+01
 25.0 TO 30.0   C.53125 -2.8813+01  0.95577  1.3333+00 -1.1418+02 -3.6258+01  2.5234+02 -1.4368+02  1.7755+00  2.9357+01
 30.0 TO 35.0   0.44323 -3.3982+01  0.96223  1.3337+00 -1.3378+02 -4.1427+01  2.54C1+02 -1.63C8+02  2.2874+00  2.9164+01
 35.0 TO 40.0   0.35845 -3.8776+01  0.96678  1.332 +00 -1.5173+02 -4.6221+01  2.5554+02 -1.8C87+02  2.8134+00  2.899 +01
 40.0 TO 45.0   0.43277 -4.2561+01  0.96625  1.4863+00 -1.6434+02 -5.7116+01  2.5897+02 -2.2055+02  4.1833+00  5.6139+01
 45.0 TO 50.0   0.37038 -4.6623+01  0.96916  1.4832+00 -1.7851+02 -6.4306+01  2.6118+02 -2.4621+02  5.2136+00  6.7693+01
 50.0 TO 55.0   0.30999 -5.0288+01  0.97144  1.4781+00 -1.9094+02 -7.156 +01  2.6337+02 -2.7171+02  6.3491+00  8.0727+01
 55.0 TO 60.0   0.47566 -5.1996+01  0.96774  1.7332+00 -1.961 +02 -7.7537+01  2.6515+02 -2.9243+02  7.3541+00  9.6315+01
 60.0 TO 65.0   0.43424 -5.4778+01  0.96957  1.7188+C0 -2.0482+02 -8.5345+01  2.6744+02 -3.1912+02  8.7578+00  1.1422+02
 65.0 TO 70.0   C.39491 -5.6695+01  0.97101  1.7012+00 -2.1129+02 -9.3319+01  2.6974+02 -3.4596+02  1.0293+01  1.3451+02
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```
SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATION = -3.25 TO -2.25 MPH/SEC

PROBABILITY =  0.03662

    VEHICLE     PROBABILITY  POWER       GEAR       TORQUE      MOTOR       MOTOR       POWER      MOTOR        MOTOR      MOTOR      TERMINAL
     SPEED                   DEMAND      LOSS      AT WHEEL     TORQUE      POWER       INPUT      EFFICIENCY   LOSS       CURRENT    VOLTAGE
      MPH                     HP          HP        FT-LB       FT-LB        HP          KW                      KW        AMPS          V

  0.0 TO  5.0   0.00607 -3.146+00  9.716 -02 -4.7192+02 -5.8543+01 -3.048+00 -8.0643-01   0.35469  1.4671+00 -1.9659+02  4.1019+00
  5.0 TO 10.0   0.00564 -9.392+00  3.0663-01 -4.6962+02 -5.8152+01 -9.085+00 -5.1315+00   0.75740  1.6436+00 -1.9568+02  2.6223+01
 10.0 TO 15.0   0.00498 -1.552+01  5.3419-01 -4.657 +02 -5.7562+01 -1.498+01 -9.4609+00   0.84643  1.7164+00 -1.943 +02  4.869 +01
 15.0 TO 20.0   0.00705 -2.147+01  7.7688-01 -4.6017+02 -5.6774+01 -2.069+01 -1.3493+01   0.87428  1.9402+00 -1.9247+02  7.0108+01
 20.0 TO 25.0   0.00690 -2.718+01  1.0313+00 -4.5301+02 -5.5789+01 -2.614+01 -1.7287+01   0.88657  2.2117+00 -1.9017+02  9.0906+01
 25.0 TO 30.0   0.00411 -3.257+01  1.2935+00 -4.4424+02 -5.4608+01 -3.128+01 -2.0916+01   0.89658  2.4124+00 -1.8741+02  1.116 +02
 30.0 TO 35.0   0.00126 -3.76 +01  1.5593+00 -4.3385+02 -5.3233+01 -3.604+01 -2.4199+01   0.90043  2.676 +00 -1.842 +02  1.3137+02
 35.0 TO 40.0   0.00035 -4.218+01  1.8238+00 -4.2184+02 -5.1664+01 -4.036+01 -2.7156+01   0.90230  2.9402+00 -1.8054+02  1.5041+02
 40.0 TO 45.0   0.00014 -4.626+01  2.0819+00 -4.0821+02 -6.6537+01 -4.418+01 -2.9765+01   0.90343  3.1816+00 -2.1525+02  1.3828+02
 45.0 TO 50.0   0.00004 -4.977+01  2.3277+00 -3.9297+02 -6.3934+01 -4.744+01 -3.1998+01   0.90437  3.3834+00 -2.0917+02  1.5297+02
 50.0 TO 55.0   0.00002 -5.265+01  2.5553+00 -3.761 +02 -6.1077+01 -5.009+01 -3.3871+01   0.90664  3.4675+00 -2.0251+02  1.6725+02
 55.0 TO 60.0   0.00006 -5.483+01  2.7579+00 -3.5762+02 -8.6952+01 -5.207+01 -3.4886+01   0.89839  3.9458+00 -2.6289+02  1.3271+02
 60.0 TO 65.0 +00.00000 -5.625+01  2.9285+00 -3.3752+02 -8.1911+01 -5.332+01 -3.5969+01   0.90457  3.7545+00 -2.5112+02  1.4323+02
 65.0 TO 70.0 +00.00000 -5.684+01  3.0595+00 -3.158 +02 -7.6497+01 -5.378+01 -3.633 +01   0.90583  3.7766+00 -2.3849+02  1.5233+02

    VEHICLE      ALPHA       PCU        PCU          PCU      PCU INPUT    BATTERY    BATTERY    BATTERY      BATTERY    RECTIFIER
     SPEED                   POWER      EFFICIENCY   LOSS     CURRENT      POWER      VOLTAGE    CURRENT      LOSS       CURRENT
      MPH                    KW                      KW       AMPS         KW           V        AMPS         KW         AMPS

  0.0 TO  5.0   1.00000  0.      +00   0.00000  8.0643-01  0.      +00 -7.445 +00  2.4263+02 -3.0683+01  8.0967-02  3.0533+01
  5.0 TO 10.0   0.91704 -3.5612+00   0.77193  1.1703+00 -1.6233+01 -1.1406+01  2.4402+02 -4.6742+01  1.879 -01  3.0359+01
 10.0 TO 15.0   0.82628 -8.287 +00   0.87591  1.1739+00 -3.3755+01 -1.5732+01  2.455 +02 -6.408 +01  3.5314-01  3.0175+01
 15.0 TO 20.0   0.74076 -1.2318+01   0.91286  1.1757+00 -4.9895+01 -1.9763+01  2.4687+02 -8.0052+01  5.5112-01  3.0008+01
 20.0 TO 25.0   0.65855 -1.6111+01   0.93197  1.1759+00 -6.4925+01 -2.3556+01  2.4815+02 -9.4926+01  7.7495-01  2.9852+01
 25.0 TO 30.0   0.57759 -1.9741+01   0.94384  1.1745+00 -7.9166+01 -2.7186+01  2.4936+02 -1.0902+02  1.0221+00  2.9708+01
 30.0 TO 35.0   0.50066 -2.3028+01   0.95159  1.1713+00 -9.1945+01 -3.0473+01  2.5045+02 -1.2167+02  1.2731+00  2.9579+01
 35.0 TO 40.0   0.42746 -2.599 +01   0.95705  1.1662+00 -1.0337+02 -3.3435+01  2.5142+02 -1.3298+02  1.5208+00  2.9465+01
 40.0 TO 45.0   0.47596 -2.8493+01   0.95726  1.2719+00 -1.1193+02 -4.3047+01  2.5454+02 -1.6911+02  2.4596+00  5.7115+01
 45.0 TO 50.0   0.42663 -3.0734+01   0.96048  1.2645+00 -1.1993+02 -4.8417+01  2.5625+02 -1.8894+02  3.0701+00  6.8993+01
 50.0 TO 55.0   0.37567 -3.2616+01   0.96293  1.2554+00 -1.2643+02 -5.3888+01  2.5797+02 -2.0889+02  3.7527+00  8.2417+01
 55.0 TO 60.0   0.50952 -3.3466+01   0.95926  1.4213+00 -1.2893+02 -5.9007+01  2.5956+02 -2.2733+02  4.4467+00  9.8391+01
 60.0 TO 65.0   0.47344 -3.4568+01   0.96104  1.401 +00 -1.3223+02 -6.5135+01  2.6143+02 -2.4915+02  5.3386+00  1.1685+02
 65.0 TO 70.0   0.44334 -3.4952+01   0.96208  1.3776+00 -1.3275+02 -7.1277+01  2.6328+02 -2.7073+02  6.3032+00  1.3782+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATION = -2.25 TO -1.25 MPH/SEC

PROBABILITY =  0.05685

  VEHICLE    PROBABILITY  POWER      GEAR      TORQUE      MOTOR      MOTOR      POWER       MOTOR       MOTOR      MOTOR      TERMINAL
   SPEED                  DEMAND     LOSS      AT WHEEL    TORQUE     POWER      INPUT     EFFICIENCY    LOSS       CURRENT     VOLTAGE
    MPH                    HP         HP        FT-LB      FT-LB       HP         KW                      KW        AMPS          V


  0.0 TO  5.0   0.00944 -1.84 +00  5.6837-02 -2.7606+02 -3.4246+01 -1.783+00 -3.6995-01    0.27816  9.6003-01 -1.399 +02  2.6443+00
  5.0 TO 10.0   0.00600 -5.475+00  1.7875-01 -2.7376+02 -3.3899+01 -5.276+00 -2.6221+00    0.66391  1.3273+00 -1.3909+02  1.8851+01
 10.0 TO 15.0   0.00483 -8.994+00  3.0953-01 -2.6984+02 -3.3353+01 -8.685+00 -5.2564+00    0.81160  1.2201+00 -1.3782+02  3.8138+01
 15.0 TO 20.0   0.00675 -1.233+01  4.4621-01 -2.6431+02 -3.2609+01 -1.188+01 -7.6133+00    0.85881  1.2516+00 -1.3608+02  5.5944+01
 20.0 TO 25.0   0.01054 -1.542+01  5.8541-01 -2.5715+02 -3.1669+01 -1.484+01 -9.5924+00    0.86659  1.4766+00 -1.3389+02  7.1642+01
 25.0 TO 30.0   0.01077 -1.821+01  7.2325-01 -2.4838+02 -3.0532+01 -1.749+01 -1.1352+01    0.87036  1.6506+00 -1.3124+02  8.65  +01
 30.0 TO 35.0   0.00508 -2.062+01  8.5539-01 -2.3799+02 -2.9201+01 -1.977+01 -1.2808+01    0.86860  1.9342+00 -1.2813+02  9.9961+01
 35.0 TO 40.0   0.00148 -2.259+01  9.7706-01 -2.2598+02 -2.7677+01 -2.162+01 -1.3928+01    0.86391  2.1541+00 -1.2457+02  1.118 +02
 40.0 TO 45.0   0.00118 -2.406+01  1.083 +00 -2.1235+02 -3.4613+01 -2.298+01 -1.5066+01    0.87908  2.0724+00 -1.4076+02  1.0703+02
 45.0 TO 50.0   0.00082 -2.496+01  1.1676+00 -1.971 +02 -3.2069+01 -2.379+01 -1.5499+01    0.87335  2.2477+00 -1.3482+02  1.1496+02
 50.0 TO 55.0   0.00075 -2.523+01  1.2246+00 -1.8024+02 -2.927 +01 -2.4   +01 -1.5519+01    0.86683  2.3841+00 -1.2829+02  1.2096+02
 55.0 TO 60.0   0.00050 -2.48 +01  1.2475+00 -1.6176+02 -3.933 +01 -2.355+01 -1.5582+01    0.88711  1.9829+00 -1.5177+02  1.0267+02
 60.0 TO 65.0   0.00027 -2.361+01  1.2291+00 -1.4165+02 -3.4379+01 -2.238+01 -1.4665+01    0.87875  2.0235+00 -1.4021+02  1.0459+02
 65.0 TO 70.0   0.00004 -2.158+01  1.162 +00 -1.1993+02 -2.9053+01 -2.042+01 -1.3222+01    0.86802  2.0102+00 -1.2779+02  1.0346+02

  VEHICLE       ALPHA      PCU        PCU         PCU      PCU INPUT   BATTERY    BATTERY    BATTERY    BATTERY    RECTIFIER
   SPEED                   POWER    EFFICIENCY    LOSS      CURRENT     POWER     VOLTAGE    CURRENT     LOSS       CURRENT
    MPH                     KW                     KW        AMPS        KW          V         AMPS       KW         AMPS


  0.0 TO  5.0   1.00000  0.     +00    0.00000  3.6995-01  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.0967-02  3.0533+01
  5.0 TO 10.0   0.95268 -1.6008+00    0.61050  1.0213+00 -6.5817+00 -9.0458+00  2.4322+02 -3.7191+01  1.1895-01  3.0458+01
 10.0 TO 15.0   0.87414 -4.2346+00    0.80561  1.0217+00 -1.7346+01 -1.1679+01  2.4412+02 -4.7843+01  1.9685-01  3.0346+01
 15.0 TO 20.0   0.80220 -6.5928+00    0.86595  1.0205+00 -2.6918+01 -1.4037+01  2.4492+02 -5.7315+01  2.8251-01  3.0247+01
 20.0 TO 25.0   0.73924 -8.5748+00    0.89392  1.0175+00 -3.4913+01 -1.6019+01  2.456 +02 -6.5227+01  3.6589-01  3.0163+01
 25.0 TO 30.0   0.68001 -1.0339+01    0.91076  1.013 +00 -4.1995+01 -1.7784+01  2.462 +02 -7.2234+01  4.4873-01  3.009 +01
 30.0 TO 35.0   0.62665 -1.1801+01    0.92140  1.0067+00 -4.7839+01 -1.9247+01  2.4669+02 -7.8017+01  5.2346-01  3.0029+01
 35.0 TO 40.0   0.57593 -1.293 +01    0.92829  9.9877-01 -5.2331+01 -2.0375+01  2.4708+02 -8.2463+01  5.8481-01  2.9983+01
 40.0 TO 45.0   0.60153 -1.4013+01    0.93007  1.0535+00 -5.609 +01 -2.8567+01  2.4983+02 -1.1434+02  1.1244+00  5.8192+01
 45.0 TO 50.0   0.57282 -1.4457+01    0.93274  1.0425+00 -5.7594+01 -3.214 +01  2.5101+02 -1.2804+02  1.4099+00  7.0433+01
 50.0 TO 55.0   0.55216 -1.449 +01    0.93365  1.0296+00 -5.7455+01 -3.5762+01  2.5219+02 -1.418 +02  1.7293+00  8.4304+01
 55.0 TO 60.0   0.62366 -1.4483+01    0.92946  1.0992+00 -5.7117+01 -4.0024+01  2.5357+02 -1.5784+02  2.1425+00  1.0071+02
 60.0 TO 65.0   0.61970 -1.3592+01    0.92680  1.0734+00 -5.3324+01 -4.4159+01  2.549 +02 -1.7324+02  2.5811+00  1.1984+02
 65.0 TO 70.0   0.62817 -1.2177+01    0.92097  1.0448+00 -4.7515+01 -4.8501+01  2.5628+02 -1.8925+02  3.0802+00  1.4158+02
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SERIES
WITH GEARING
P(IC) =  16 HP
K(B) =  .086 OHMS

ACCELERATION = -1.25 TO -0.75 MPH/SEC

PROBABILITY =  0.08253

  VEHICLE    PROBABILITY  POWER       GEAR      TORQUE      MOTOR      MOTOR      POWER        MOTOR      MOTOR       MOTOR    TERMINAL
   SPEED                  DEMAND      LOSS     AT WHEEL     TORQUE     POWER      INPUT      EFFICIENCY    LOSS      CURRENT    VOLTAGE
    MPH                    HP          HP       FT-LB       FT-LB       HP         KW                       KW        AMPS         V


  0.0 TO  5.0  0.00596 -8.61 -01  2.6592-02 -1.2916+02 -1.6023+01 -8.344-01 -1.2952-01   0.20814  4.9275-01 -9.7387+01  1.33   +00
  5.0 TO 10.0  0.00423 -2.537+00  6.2837-02 -1.2686+02 -1.5709+01 -2.454+00 -1.0054+00   0.54534  8.2484-01 -9.6655+01  1.0402+01
 10.0 TO 15.0  0.00294 -4.098+00  1.4105-01 -1.2294+02 -1.5196+01 -3.957+00 -2.2287+00   0.75526  7.2221-01 -9.5459+01  2.3347+01
 15.0 TO 20.0  0.00562 -5.479+00  1.9822-01 -1.1741+02 -1.4486+01 -5.281+00 -3.2358+00   0.82166  7.023 -01 -9.38   +01  3.4496+01
 20.0 TO 25.0  0.01241 -6.615+00  2.51   -01 -1.1026+02 -1.3578+01 -6.304+00 -3.8065+00   0.80202  9.356 -01 -9.1683+01  4.1518+01
 25.0 TO 30.0  0.02063 -7.442+00  2.9551-01 -1.0148+02 -1.2475+01 -7.147+00 -4.0806+00   0.76567  1.2468+00 -8.9109+01  4.5794+01
 30.0 TO 35.0  0.01543 -7.895+00  3.2742-01 -9.1098+01 -1.1177+01 -7.567+00 -4.0513+00   0.71791  1.5518+00 -8.6081+01  4.7064+01
 35.0 TO 40.0  0.00619 -7.908+00  3.4194-01 -7.9089+01 -9.6863+00 -7.566+00 -3.6839+00   0.65286  1.9587+00 -8.2601+01  4.4599+01
 40.0 TO 45.0  0.00257 -7.418+00  3.3385-01 -6.5461+01 -1.067 +01 -7.035+00 -3.7142+00   0.70300  1.5691+00 -8.4896+01  4.375 +01
 45.0 TO 50.0  0.00213 -6.36 +00  2.9745-01 -5.0215+01 -6.1698+00 -6.063+00 -2.7522+00   0.60872  1.765 +00 -7.9062+01  3.481 +01
 50.0 TO 55.0  0.00170 -4.669+00  2.2659-01 -3.335 +01 -5.416 +00 -4.442+00 -1.6342+00   0.49332  1.6785+00 -7.2637+01  2.2499+01
 55.0 TO 60.0  0.00148 -2.279+00  1.1465-01 -1.4867+01 -3.6148+00 -2.165+00 -7.9149-01   0.49025  8.2256-01 -6.8434+01  1.1565+01
 60.0 TO 65.0  0.00107  8.723-01  4.7909-02  5.2343+00  1.4136+00  9.203-01  0.    +00   0.00000 -6.8626-01  6.3298+01  0.    +00
 65.0 TO 70.0  0.00017  4.651+00  2.7599-01  2.6954+01  7.2934+00  5.127+00  6.5143+00   0.58698  2.6505+00  7.7017+01  8.4582+01

  VEHICLE      ALPHA      PCU          PCU        PCU      PCU INPUT   BATTERY    BATTERY    BATTERY    BATTERY   RECTIFIER
   SPEED                  POWER     EFFICIENCY    LOSS      CURRENT     POWER     VOLTAGE    CURRENT     LOSS      CURRENT
    MPH                    KW                      KW         AMPS        KW         V         AMPS        KW        AMPS


  0.0 TO  5.0  1.00000  0.    +00     0.00000  1.2952-01  0.    +00 -7.445 +00  2.4263+02 -3.0683+01  8.0967-02  3.0533+01
  5.0 TO 10.0  0.99579 -9.8662-02     0.09812  9.0679-01 -4.065 -01 -7.5436+00  2.427 +02 -3.1081+01  8.3079-02  3.0523+01
 10.0 TO 15.0  0.94298 -1.3236+00     0.59390  9.0507-01 -5.4446+00 -8.7686+00  2.4311+02 -3.6068+01  1.1188-01  3.0472+01
 15.0 TO 20.0  0.89780 -2.3339+00     0.72127  9.019 -01 -9.5864+00 -9.7789+00  2.4346+02 -4.0166+01  1.3874-01  3.0429+01
 20.0 TO 25.0  0.86975 -2.9096+00     0.76437  8.969 -01 -1.1941+01 -1.0354+01  2.4365+02 -4.2496+01  1.5531-01  3.0404+01
 25.0 TO 30.0  0.85311 -3.1903+00     0.78182  8.9028-01 -1.3088+01 -1.0635+01  2.4375+02 -4.3631+01  1.6371-01  3.0392+01
 30.0 TO 35.0  0.84856 -3.1693+00     0.78227  8.8208-01 -1.3001+01 -1.0614+01  2.4376+02 -4.3544+01  1.6306-01  3.0391+01
 35.0 TO 40.0  0.86028 -2.8117+00     0.76325  8.7217-01 -1.154 +01 -1.0256+01  2.4363+02 -4.2098+01  1.5241-01  3.0407+01
 40.0 TO 45.0  0.86468 -2.8269+00     0.76112  8.8723-01 -1.1488+01 -1.7381+01  2.4608+02 -7.0634+01  4.2906-01  5.9079+01
 45.0 TO 50.0  0.90374 -1.8784+00     0.68250  8.7381-01 -7.6102+00 -1.9561+01  2.4682+02 -7.9252+01  5.4016-01  7.1628+01
 50.0 TO 55.0  0.95651 -7.752 -01     0.47433  8.5907-01 -3.1294+00 -2.2047+01  2.4771+02 -8.9005+01  6.8128-01  8.583 +01
 55.0 TO 60.0  1.00000  0.    +00     0.00000  7.9149-01  0.    +00 -2.554 +01  2.4882+02 -1.0264+02  9.0609-01  1.0263+02
 60.0 TO 65.0  0.05561  0.    +00     0.00050  0.    +00  3.5204+00 -3.0567+01  0.    +00  0.    +00  0.    +00  0.    +00
 65.0 TO 70.0  0.38669  7.4433+00     0.87519  9.2894-01  2.9782+01 -2.8881+01  2.4992+02 -1.1556+02  1.1484+00  1.4518+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .C86 CHMS

ACCELERATION = -C.75 TO -0.25 MPH/SEC

PROBABILITY =  0.13537

   VEHICLE     PROBABILITY  POWER       GEAR       TORQUE      MOTOR       MOTOR       POWER       MOTCR       MCTOR       MOTOR      TERMINAL
    SPEED                   DEMAND      LOSS      AT WHEEL     TORQUE      POWER       INPUT    EFFICIENCY     LCSS       CURRENT     VOLTAGE
     MPH                     HP          HP        FT-LB       FT-LB        HP          KW                     KW         AMPS          V

  0.0 TO  5.0   0.C0914 -2.082-01  6.4306-03 -3.1233+01 -3.8747+00 -2.017-01 -3.3115-02   0.22006  1.1736-01 -6.904 +01  4.7964-01
  5.0 TO 10.0   0.C0589 -5.787-01  1.8893-02 -2.8936+01 -3.5831+00 -5.598-01 -2.0016-01   C.47948  2.1729-01 -6.836 +01  2.928 +00
 10.0 TO 15.0   C.00306 -8.339-01  2.8699-02 -2.5C19+01 -3.0925+00 -8.052-01 -3.1092-01   0.51777  2.8558-01 -6.7215+01  4.6257+00
 15.0 TO 20.0   C.CC73C -9.092-01  3.2895-02 -1.9484+C1 -2.4039+00 -8.763-01 -3.2745-01   0.50105  3.26C7-01 -6.5609+01  4.9909+00
 20.0 TO 25.0   0.01884 -7.398-01  2.8072-02 -1.2331+C1 -1.5186+00 -7.118-01  0.     +00   0.00000  5.308 -01 -6.3543+01  0.     +00
 25.0 TO 30.0   0.03052 -2.61  -01  1.0364-02 -3.5594+00 -4.3755-01 -2.506-01  0.     +00   0.00000  1.8652-01 -6.102 +01  0.     +00
 30.0 TO 35.0   0.02744  5.92  -01  2.5613-02  6.831 +00  9.1226-01  6.176-01  0.     +00   0.00000 -4.6057-01  6.2128+01  0.     +00
 35.0 TO 40.0   0.01215  1.884+00  8.5135-02  1.684 +01  2.5206+00  1.969+00  3.6349+00   0.40396  2.1665+00  6.5881+01  5.5173+01
 40.0 TO 45.0   0.00433  3.679+00  1.7338-01  3.2467+01  5.8026+00  3.853+00  5.2627+00   0.54595  2.3855+00  7.3539+01  7.1564+01
 45.0 TO 50.0   C.0C322  6.043+00  2.9649-01  4.7713+C1  8.5432+00  6.34 +00  7.6095+00   0.62131  2.8816+00  7.9933+01  9.5198+01
 50.0 TO 55.0   0.004C6  9.04 +00  4.6112-01  6.4578+01  1.1584+01  9.502+00  9.9269+00   C.71379  2.8411+00  8.7029+01  1.1406+02
 55.0 TO 60.0   0.00656  1.273+01  6.7446-01  8.3061+01  2.2391+01  1.341+01  1.1676+01   0.85641  1.6766+00  1.1224+02  1.0403+02
 60.0 TO 65.0   0.00234  1.719+01  9.4422-01  1.0316+02  2.7862+01  1.813+01  1.5603+01   0.86684  2.0776+00  1.2501+02  1.2481+02
 65.0 TO 70.0   C.00052  2.247+01  1.2787+00  1.2488+02  3.3791+01  2.375+01  2.0196+01   0.87719  2.48C3+00  1.3884+02  1.4546+02

   VEHICLE      ALPHA       PCU        PCU         PCU       PCU INPUT    BATTERY     BATTERY     BATTERY     BATTERY   RECTIFIER
    SPEED                   POWER   EFFICIENCY     LOSS       CURRENT      POWER      VOLTAGE     CURRENT      LOSS      CURRENT
     MPH                     KW                    KW         AMPS         KW          V          AMPS         KW         AMPS

  0.0 TO  5.0   1.C0000  0.     +00   0.00000  3.3115-02  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.C967-02  3.0533+01
  5.0 TO 10.0   1.00000  0.     +00   0.00000  2.0016-01  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.C967-02  3.0533+01
 10.0 TO 15.0   1.00000  0.     +00   0.00000  3.1092-01  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.C967-02  3.0533+01
 15.0 TO 20.0   1.00000  0.     +00   0.00000  3.2745-01  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.0967-02  3.0533+01
 20.0 TO 25.0   1.0C000  0.     +00   0.00000  0.     +00  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.C967-02  3.0533+01
 25.0 TO 30.0   1.C0000  0.     +00   0.00000  0.     +00  0.     +00 -7.445 +00  2.4263+02 -3.0683+01  8.C967-02  3.0533+01
 30.0 TO 35.0   0.C5637  0.     +00   0.00021  0.     +00  3.5025+00 -7.445 +00  0.     +00  0.     +00  0.     +00  0.     +00
 35.0 TO 40.0   0.28285  4.492 +00   0.80918  8.5716-01  1.8634+01 -2.9529+00  2.4106+02 -1.2249+01  1.2904-02  3.0732+01
 40.0 TO 45.0   0.34440  6.1535+00   0.85523  8.908 -01  2.5327+01 -8.4011+00  2.4296+02 -3.4577+01  [illegible]  5.9838+01
 45.0 TO 50.0   0.43840  8.5239+00   0.89272  9.1442-01  3.5043+01 -9.1593+00  2.4324+02 -3.7655+01  1.2193-01  7.2684+01
 50.0 TO 55.0   C.51249  1.0868+01   0.91339  9.4125-01  4.4602+01 -1.0404+01  2.4366+02 -4.2648+01  1.5679-01  8.7255+01
 55.0 TO 60.0   0.46318  1.2712+01   0.91853  1.0356+00  5.199 +01 -1.2828+01  2.4452+02 -5.2463+01  2.367 -01  1.0444+02
 60.0 TO 65.0   C.54512  1.6687+01   0.93504  1.0839+00  6.8145+01 -1.3879+01  2.4487+02 -5.6681+01  2.7629-01  1.2474+02
 65.0 TO 70.0   0.62649  2.1333+01   0.94670  1.1369+00  8.6985+01 -1.499 +01  2.4525+02 -6.1124+01  3.2131-01  1.4795+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATION = -0.25 TO  0.25 MPH/SEC

PROBABILITY =  0.30668

   VEHICLE     PROBABILITY   POWER       GEAR      TORQUE      MOTOR      MOTOR      POWER       MOTOR       MOTOR      MOTOR      TERMINAL
    SPEED                    DEMAND      LOSS     AT WHEEL     TORQUE     POWER      INPUT     EFFICIENCY    LOSS      CURRENT     VOLTAGE
     MPH                       HP         HP        FT-LB      FT-LB        HP        KW                      KW        AMPS          V

  0.0 TO  5.0   0.13143   4.446-01  1.4168-02  6.6695+01  6.8096+00  4.588-01  1.6059+00   0.21303  1.2638+00  8.0555+01  1.9936+01
  5.0 TO 10.0   0.00558   1.379+00  4.6567-02  6.8993+01  9.1297+00  1.426+00  2.0805+00   0.51125  1.0168+00  8.1302+01  2.559 +01
 10.0 TO 15.0   0.00307   2.43 +00  8.661 -02  7.2409+01  9.6656+00  2.516+00  2.894 +00   0.64853  1.0171+00  8.2552+01  3.5056+01
 15.0 TO 20.0   0.00491   3.66 +00  1.374 -01  7.8444+01  1.0418+01  3.798+00  3.9683+00   0.71372  1.136 +00  8.4309+01  4.7068+01
 20.0 TO 25.0   0.01665   5.135+00  2.0254-01  8.5597+01  1.1389+01  5.338+00  5.3852+00   0.73921  1.4043+00  8.6574+01  6.2203+01
 25.0 TO 30.0   0.03470   6.92 +00  2.8614-01  9.4369+01  1.2579+01  7.206+00  6.9896+00   0.76884  1.6157+00  8.9352+01  7.8226+01
 30.0 TO 35.0   0.04672   9.079+00  3.928 -01  1.0476+02  1.399 +01  9.472+00  8.7277+00   0.80928  1.6644+00  9.2643+01  9.4207+01
 35.0 TO 40.0   0.02670   1.167+01  5.2766-01  1.1676+02  1.5622+01  1.22 +01  1.085 +01   0.83874  1.7496+00  9.6453+01  1.1249+02
 40.0 TO 45.0   0.00731   1.477+01  6.9635-01  1.3039+02  2.3334+01  1.547+01  1.3447+01   0.85811  1.908 +00  1.1437+02  1.1757+02
 45.0 TO 50.0   0.00491   1.844+01  9.0502-01  1.4564+02  2.6077+01  1.935+01  1.6755+01   0.86129  2.324 +00  1.2084+02  1.3865+02
 50.0 TO 55.0   0.00649   2.275+01  1.1603+00  1.625 +02  2.9151+01  2.391+01  2.0576+01   0.86657  2.7453+00  1.2801+02  1.6072+02
 55.0 TO 60.0   0.01499   2.775+01  1.4696+00  1.8099+02  4.879 +01  2.922+01  2.4274+01   0.89767  2.4838+00  1.7384+02  1.3963+02
 60.0 TO 65.0   0.00442   3.351+01  1.8405+00  2.0109+02  5.431 +01  3.535+01  2.9281+01   0.90039  2.9164+00  1.8672+02  1.5681+02
 65.0 TO 70.0   0.00080   4.01 +01  2.2814+00  2.2281+02  6.0288+01  4.238+01  3.5025+01   0.90244  3.4168+00  2.0067+02  1.7454+02

   VEHICLE       ALPHA       PCU         PCU         PCU      PCU INPUT   BATTERY    BATTERY     BATTERY    BATTERY    RECTIFIER
    SPEED                   POWER     EFFICIENCY     LOSS      CURRENT     POWER     VOLTAGE     CURRENT     LOSS       CURRENT
     MPH                     KW                       KW        AMPS        KW          V         AMPS        KW         AMPS

  0.0 TO  5.0   0.12926  2.5168+00    0.63810  9.1083-01  1.9412+01 -4.9281+00  2.417 +02 -2.0389+01  3.5751-02  3.065 +01
  5.0 TO 10.0   0.15243  2.9934+00    0.69505  9.1283-01  1.2393+01 -4.4516+00  2.4153+02 -1.843 +01  2.9212-02  3.0671+01
 10.0 TO 15.0   0.19128  3.8103+00    0.75951  9.1633-01  1.5791+01 -3.6346+00  2.4129+02 -1.5062+01  1.5512-02  3.0701+01
 15.0 TO 20.0   0.24072  4.8893+00    0.81162  9.2103-01  2.0295+01 -2.5556+00  2.4091+02 -1.0608+01  9.678 -03  3.0751+01
 20.0 TO 25.0   0.30328  6.3123+00    0.85313  9.2705-01  2.6256+01 -1.1327+00  2.404 +02 -4.7116+00  1.9091-03  3.0815+01
 25.0 TO 30.0   0.36938  7.9254+00    0.88193  9.3573-01  3.3005+01  4.804 -01  2.4012+02  2.0006+00  3.4422-04  3.0851+01
 30.0 TO 35.0   0.43646  9.6713+00    0.90243  9.4361-01  4.0435+01  2.2263+00  2.3918+02  9.3083+00  7.4516-03  3.0973+01
 35.0 TO 40.0   0.51335  1.1804+01    0.91919  9.5391-01  4.9514+01  4.3595+00  2.384 +02  1.8286+01  2.8757-02  3.1074+01
 40.0 TO 45.0   0.52685  1.4472+01    0.92918  1.0248+00  6.0259+01 -8.2402-02  2.4016+02 -3.431 -01  1.0124-05  6.0535+01
 45.0 TO 50.0   0.61352  1.7803+01    0.94114  1.0479+00  7.4142+01  1.2034-01  2.4012+02  5.0115-01  2.1599-05  7.3627+01
 50.0 TO 55.0   0.70459  2.1649+01    0.95042  1.0733+00  9.02  +01  3.7691-01  2.4001+02  1.5703+00  2.1208-04  8.8583+01
 55.0 TO 60.0   0.61108  2.5517+01    0.95128  1.2431+00  1.0623+02 -2.3398-02  2.402 +02 -9.7411-02  8.1604-07  1.0631+02
 60.0 TO 65.0   0.68188  3.0572+01    0.95776  1.2912+00  1.2732+02  5.543 -03  2.4011+02  2.3084-02  4.5828-08  1.2721+02
 65.0 TO 70.0   0.75488  3.6369+01    0.96304  1.3441+00  1.5148+02  4.5164-02  2.4008+02  1.8811-01  3.0432-06  1.5113+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(3) =  .C86 OHMS

ACCELERATION =  0.25 TO  0.75 MPH/SEC

PROBABILITY =  0.11415

  VEHICLE    PROBABILITY  POWER       GEAR        TORQUE      MOTOR       MOTOR       POWER        MOTOR       MOTOR      MOTOR       TERMINAL
   SPEED                  DEMAND      LOSS       AT WHEEL     TORQUE      POWER       INPUT      EFFICIENCY    LOSS      CURRENT      VOLTAGE
    MPH                     HP         HP         FT-LB       FT-LB        HP          KW                      KW         AMPS          V


  0.0 TO  5.0   0.00621  1.097+00  3.4971-02  1.6462+02  2.1744+01  1.132+00  3.6695+00     0.23013  2.825 +00  1.1073+02  3.3137+01
  5.0 TO 10.0   0.00421  3.338+00  1.1266-01  1.6692+02  2.2088+01  3.451+00  4.3654+00     0.58952  1.7519+00  1.1153+02  3.9137+01
 10.0 TO 15.0   0.00213  5.654+00  2.0293-01  1.7083+02  2.2648+01  5.897+00  5.6499+00     0.77838  1.2521+00  1.1284+02  5.0068+01
 15.0 TO 20.0   0.00466  8.23 +00  3.3892-01  1.7637+02  2.3424+01  8.539+00  7.[illegible]23+00     0.84654  1.1543+00  1.1465+02  6.5607+01
 20.0 TO 25.0   0.01318  1.101+01  4.3426-01  1.8352+02  2.4419+01  1.144+01  9.9681+00     0.85625  1.4329+00  1.1697+02  8.5213+01
 25.0 TO 30.0   0.02777  1.41 +01  5.8307-01  1.9229+02  2.5633+01  1.468+01  1.2709+01     0.86160  1.7589+00  1.1981+02  1.0608+02
 30.0 TO 35.0   0.02655  1.756+01  7.5997-01  2.0268+02  2.7068+01  1.832+01  1.5802+01     0.86479  2.1366+00  1.2315+02  1.2831+02
 35.0 TO 40.0   0.01122  2.146+01  9.7018-01  2.1469+02  2.8725+01  2.244+01  1.932 +01     0.86610  2.5669+00  1.2702+02  1.521 +02
 40.0 TO 45.0   0.00381  2.587+01  1.2193+00  2.2832+02  4.0806+01  2.709+01  2.2668+01     0.89056  2.4829+00  1.5521+02  1.4617+02
 45.0 TO 50.0   0.00276  3.065+01  1.5135+00  2.4357+02  4.3611+01  3.236+01  2.6919+01     0.89657  2.7842+00  1.6175+02  1.6641+02
 50.0 TO 55.0   0.00337  3.646+01  1.8596+00  2.6044+02  4.6718+01  3.832+01  3.1695+01     0.90156  3.1159+00  1.69  +02  1.8754+02
 55.0 TO 60.0   0.00562  4.276+01  2.2648+00  2.7892+02  7.5189+01  4.503+01  3.7327+01     0.89962  3.7466+00  2.3544+02  1.5854+02
 60.0 TO 65.0   0.00206  4.963+01  2.7369+00  2.9902+02  8.0758+01  5.257+01  4.3333+01     0.90470  4.1253+00  2.4843+02  1.7442+02
 65.0 TO 70.0   0.00046  5.773+01  3.2841+00  3.2074+02  8.6786+01  6.191+01  5.025 +01     0.90548  4.7454+00  2.625 +02  1.9143+02

  VEHICLE       ALPHA       PCU         PCU          PCU       PCU INPUT    BATTERY      BATTERY      BATTERY      BATTERY    RECTIFIER
   SPEED                   POWER     EFFICIENCY      LOSS       CURRENT      POWER       VOLTAGE      CURRENT       LOSS       CURRENT
    MPH                     KW                       KW          AMPS         KW            V           AMPS         KW          AMPS


  0.0 TO  5.0   0.17555  4.0848+00     0.78329  1.0152+00  1.944 +01 -2.7602+00  2.4098+02 -1.1453+01  1.1282-02  3.0741+01
  5.0 TO 10.0   0.20045  5.3824+00     0.81104  1.017 +00  2.2358+01 -2.0625+00  2.4073+02 -8.5677+00  6.313 -03  3.0773+01
 10.0 TO 15.0   0.24598  6.6697+00     0.84710  1.0198+00  2.7758+01 -7.7526-01  2.4027+02 -3.2265+00  8.9529-04  3.0832+01
 15.0 TO 20.0   0.31127  8.545 +00     0.88032  1.0226+00  3.569 +01  1.1   +00  2.3942+02  4.5944+00  1.8153-03  3.0942+01
 20.0 TO 25.0   0.39381  1.0995+01     0.90652  1.0278+00  4.6367+01  3.5509+00  2.3869+02  1.4876+01  1.5032-02  3.1037+01
 25.0 TO 30.0   0.48257  1.3743+01     0.92479  1.0336+00  5.7817+01  6.2982+00  2.3769+02  2.6496+01  6.0377-02  3.1166+01
 30.0 TO 35.0   0.57812  1.6843+01     0.93822  1.0405+00  7.1201+01  9.3981+00  2.3655+02  3.9728+01  1.3574-01  3.1317+01
 35.0 TO 40.0   0.68161  2.0369+01     0.94852  1.0485+00  8.6581+01  1.2924+01  2.3525+02  5.4935+01  2.5953-01  3.1489+01
 40.0 TO 45.0   0.64926  2.3844+01     0.95151  1.1561+00  1.0077+02  9.2901+00  2.3661+02  3.9262+01  1.3257-01  6.1442+01
 45.0 TO 50.0   0.73538  2.8097+01     0.95807  1.178 +00  1.1895+02  1.0414+01  2.362 +02  4.409 +01  1.6718-01  7.485 +01
 50.0 TO 55.0   0.82568  3.2898+01     0.96345  1.2023+00  1.3954+02  1.1625+01  2.3575+02  4.9313+01  2.0913-01  9.0185+01
 55.0 TO 60.0   0.70037  3.8776+01     0.96264  1.4466+00  1.6489+02  1.3235+01  2.3515+02  5.6283+01  2.7243-01  1.086 +02
 60.0 TO 65.0   0.76864  4.483 +01     0.96661  1.4965+00  1.9095+02  1.4263+01  2.3476+02  6.0754+01  3.1743-01  1.3012+02
 65.0 TO 70.0   0.84220  5.1798+01     0.97010  1.5483+00  2.2107+02  1.5474+01  2.343 +02  6.6045+01  3.7512-01  1.5486+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATION =  0.75 TO  1.25 MPH/SEC

PROBABILITY =  0.06481

  VEHICLE    PROBABILITY  POWER      GEAR        TORQUE      MOTOR       MOTOR      POWER         MOTOR        MOTOR      MOTOR      TERMINAL
   SPEED                  DEMAND     LOSS        AT WHEEL    TORQUE      POWER      INPUT       EFFICIENCY     LOSS       CURRENT     VOLTAGE
    MPH                    HP         HP          FT-LB       FT-LB       HP         KW                         KW         AMPS         V

  0.0 TO  5.0  0.00485  1.75 +00   5.5775-02  2.6255+02  3.468 +01  1.806+00  4.813 +00    0.27983  3.4661+00  1.4091+02  3.4154+01
  5.0 TO 10.0  0.00255  5.297+00   1.7876-01  2.6485+02  3.5047+01  5.475+00  6.084 +00    0.67114  2.0007+00  1.4177+02  4.2913+01
 10.0 TO 15.0  0.00232  8.958+00   3.1927-01  2.6877+02  3.563 +01  9.278+00  8.4512+00    0.81866  1.5324+00  1.4313+02  5.9043+01
 15.0 TO 20.0  0.00493  1.28 +01   4.8045-01  2.743 +02  3.6431+01  1.328+01  1.1463+01    0.86391  1.5601+00  1.45  +02  7.9059+01
 20.0 TO 25.0  0.01136  1.688+01   6.6597-01  2.8146+02  3.7449+01  1.755+01  1.4962+01    0.87484  1.8725+00  1.4738+02  1.0151+02
 25.0 TO 30.0  0.01703  2.128+01   8.7999-01  2.9023+02  3.8687+01  2.216+01  1.8675+01    0.88495  2.1485+00  1.5027+02  1.2428+02
 30.0 TO 35.0  0.01065  2.605+01   1.1271+00  3.0062+02  4.0146+01  2.718+01  2.2789+01    0.88938  2.5207+00  1.5367+02  1.4829+02
 35.0 TO 40.0  0.00391  3.126+01   1.4127+00  3.1263+02  4.1827+01  3.267+01  2.7271+01    0.89345  2.9056+00  1.5759+02  1.7304+02
 40.0 TO 45.0  0.00191  3.697+01   1.7422+00  3.2626+02  5.8338+01  3.871+01  3.2027+01    0.90148  3.1551+00  1.9605+02  1.6336+02
 45.0 TO 50.0  0.00137  4.325+01   2.1221+00  3.415 +02  6.1146+01  4.537+01  3.7447+01    0.90363  3.6066+00  2.0267+02  1.8476+02
 50.0 TO 55.0  0.00139  5.017+01   2.5589+00  3.5837+02  6.4284+01  5.273+01  4.3315+01    0.90778  3.9543+00  2.0999+02  2.0626+02
 55.0 TO 60.0  0.00134  5.778+01   3.06  +00  3.7685+02  1.0158+02  6.084+01  5.0589+01    0.89685  5.2181+00  2.9704+02  1.7031+02
 60.0 TO 65.0  0.00059  6.615+01   3.6332+00  3.9695+02  1.072 +02  6.979+01  5.7721+01    0.90164  5.6773+00  3.1015+02  1.861 +02
 65.0 TO 70.0  0.00017  7.536+01   4.2868+00  4.1867+02  1.1328+02  7.964+01  6.5668+01    0.90417  6.2548+00  3.2433+02  2.0253+02

  VEHICLE       ALPHA     PCU        PCU         PCU       PCU INPUT    BATTERY     BATTERY     BATTERY     BATTERY    RECTIFIER
   SPEED                  POWER    EFFICIENCY    LOSS       CURRENT      POWER      VOLTAGE     CURRENT      LOSS       CURRENT
    MPH                    KW                     KW         AMPS         KW          V          AMPS         KW         AMPS

  0.0 TO  5.0  0.17511  5.9357+00    0.81085  1.1227+00  2.4676+01 -1.5092+00  2.4054+02 -6.2745+00  3.3857-03  3.0798+01
  5.0 TO 10.0  0.21174  7.2078+00    0.84409  1.1237+00  3.002 +01 -2.3716-01  2.4009+02 -9.8778-01  8.2911-05  3.0855+01
 10.0 TO 15.0  0.27967  9.5757+00    0.88256  1.1245+00  4.0032+01  2.1307+00  2.392 +02  8.9079+00  6.8242-03  3.097 +01
 15.0 TO 20.0  0.36463  1.259 +01    0.91054  1.1262+00  5.2874+01  5.1451+00  2.3811+02  2.1607+01  4.0153-02  3.1112+01
 20.0 TO 25.0  0.46098  1.609 +01    0.92984  1.1287+00  6.794 +01  8.6458+00  2.3683+02  3.6505+01  1.146 -01  3.1279+01
 25.0 TO 30.0  0.55983  1.9808+01    0.94281  1.1326+00  8.4125+01  1.2363+01  2.3546+02  5.2507+01  2.371 -01  3.1462+01
 30.0 TO 35.0  0.66560  2.3927+01    0.95246  1.1374+00  1.0228+02  1.6482+01  2.3392+02  7.0459+01  4.2694-01  3.1669+01
 35.0 TO 40.0  0.77644  2.8415+01    0.95976  1.1431+00  1.2236+02  2.097 +01  2.3221+02  9.0303+01  7.013 -01  3.1902+01
 40.0 TO 45.0  0.72909  3.3314+01    0.96134  1.2877+00  1.4293+02  1.876 +01  2.3306+02  8.0491+01  5.5718-01  6.2378+01
 45.0 TO 50.0  0.82354  3.8755+01    0.96626  1.3073+00  1.6691+02  2.1071+01  2.3219+02  9.0752+01  7.0829-01  7.6143+01
 50.0 TO 55.0  0.91914  4.4644+01    0.97022  1.3254+00  1.9301+02  2.3372+01  2.313 +02  1.0104+02  8.781 -01  9.192 +01
 55.0 TO 60.0  0.76467  5.2244+01    0.96832  1.6547+00  2.2713+02  2.6703+01  2.3   +02  1.1609+02  1.1591+00  1.1103+02
 60.0 TO 65.0  0.83606  5.9421+01    0.97138  1.7006+00  2.593 +02  2.8854+01  2.2916+02  1.2591+02  1.3634+00  1.333 +02
 65.0 TO 70.0  0.91056  6.7438+01    0.97404  1.7504+00  2.9545+02  3.1114+01  2.2825+02  1.3631+02  1.5879+00  1.5896+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(3) =  .066 OHMS

ACCELERATION =  1.25 TO  2.25 MPH/SEC

PROBABILITY =  0.07667

   VEHICLE     PROBABILITY  POWER       GEAR        TORQUE       MOTOR        MOTOR        POWER        MOTOR       MOTOR       MOTOR       TERMINAL
    SPEED                   DEMAND      LOSS        AT WHEEL     TORQUE       POWER        INPUT      EFFICIENCY    LOSS        CURRENT     VOLTAGE
     MPH                     HP          HP          FT-LB        FT-LB        HP           KW                      KW          AMPS         V

  0.0 TO  5.0   0.00701    2.724+00   8.6982-02   4.0545+02   5.4083+01   2.816+00   6.1217+00    0.34310   4.0213+00   1.8619+02   3.2878+01
  5.0 TO 10.0   0.00480    8.234+00   2.7791-01   4.1175+02   5.4485+01   8.512+00   8.4546+00    0.75083   2.1066+00   1.8713+02   4.518 +01
 10.0 TO 15.0   0.00532    1.385+01   4.9377-01   4.1566+02   5.5104+01   1.434+01   1.2637+01    0.84669   1.9374+00   1.8857+02   6.7016+01
 15.0 TO 20.0   0.01060    1.965+01   7.3773-01   4.212 +02   5.594 +01   2.039+01   1.7392+01    0.87436   2.1851+00   1.9052+02   9.1287+01
 20.0 TO 25.0   0.01840    2.57 +01   1.0135+00   4.2835+02   5.6994+01   2.671+01   2.2467+01    0.88668   2.5459+00   1.9298+02   1.1641+02
 25.0 TO 30.0   0.01621    3.205+01   1.3253+00   4.3712+02   5.8268+01   3.338+01   2.7759+01    0.89671   2.867 +00   1.9595+02   1.4165+02
 30.0 TO 35.0   0.00823    3.878+01   1.6779+00   4.4751+02   5.9763+01   4.046+01   3.3452+01    0.90194   3.2801+00   1.9944+02   1.6772+02
 35.0 TO 40.0   0.00277    4.595+01   2.0765+00   4.5952+02   6.149 +01   4.802+01   3.9549+01    0.90558   3.7339+00   2.0345+02   1.9438+02
 40.0 TO 45.0   0.00105    5.362+01   2.5267+00   4.7315+02   8.4561+01   5.615+01   4.6285+01    0.90462   4.4142+00   2.5731+02   1.7988+02
 45.0 TO 50.0   0.00055    6.186+01   3.0349+00   4.884 +02   8.7447+01   6.489+01   5.3336+01    0.90734   4.9416+00   2.6404+02   2.0199+02
 50.0 TO 55.0   0.00054    7.073+01   3.6078+00   5.0526+02   9.0635+01   7.434+01   6.084 +01    0.91121   5.4019+00   2.7148+02   2.241 +02
 55.0 TO 60.0   0.00060    8.03 +01   4.2528+00   5.2374+02   1.4118+02   8.456+01   7.0709+01    0.89177   7.6524+00   3.8943+02   1.8156+02
 60.0 TO 65.0   0.00055    9.064+01   4.9776+00   5.4385+02   1.4687+02   9.561+01   7.9649+01    0.89520   8.347 +00   4.0271+02   1.9778+02
 65.0 TO 70.0   0.00004    1.018+02   5.7909+00   5.6557+02   1.5303+02   1.075+02   8.9353+01    0.89791   9.1219+00   4.1707+02   2.1424+02

   VEHICLE       ALPHA      PCU          PCU          PCU        PCU INPUT    BATTERY     BATTERY      BATTERY     BATTERY     RECTIFIER
    SPEED                   POWER     EFFICIENCY      LOSS        CURRENT      POWER      VOLTAGE      CURRENT      LOSS        CURRENT
     MPH                     KW                       KW          AMPS          KW          V           AMPS         KW          AMPS

  0.0 TO  5.0   0.16581    7.4104+00    0.82609   1.2887+00   3.0873+01  -3.457 -02   2.4002+02  -1.4402-01   1.784 -06   3.0864+01
  5.0 TO 10.0   0.21769    9.7421+00    0.86784   1.2875+00   4.0738+01   2.2971+00   2.3914+02   9.6058+00   7.9353-03   3.0978+01
 10.0 TO 15.0   0.31069    1.3922+01    0.90772   1.2847+00   5.859 +01   6.4773+00   2.3762+02   2.7259+01   6.3902-02   3.1176+01
 15.0 TO 20.0   0.41554    1.8675+01    0.93132   1.2826+00   7.9171+01   1.123 +01   2.3588+02   4.7609+01   1.9493-01   3.1406+01
 20.0 TO 25.0   0.52592    2.3748+01    0.94604   1.2813+00   1.0149+02   1.6303+01   2.3398+02   6.9677+01   4.1752-01   3.1661+01
 25.0 TO 30.0   0.63865    2.904 +01    0.95587   1.2813+00   1.2518+02   2.1595+01   2.3197+02   9.3095+01   7.4533-01   3.1935+01
 30.0 TO 35.0   0.75756    3.4734+01    0.96309   1.2819+00   1.5117+02   2.7289+01   2.2976+02   1.1877+02   1.2131+00   3.2242+01
 35.0 TO 40.0   0.88273    4.0831+01    0.96857   1.2829+00   1.7959+02   3.3386+01   2.2735+02   1.4684+02   1.8545+00   3.2586+01
 40.0 TO 45.0   0.81628    4.7768+01    0.96894   1.4832+00   2.1003+02   3.3214+01   2.2743+02   1.4603+02   1.8341+00   6.3923+01
 45.0 TO 50.0   0.91952    5.4834+01    0.97267   1.4983+00   2.4279+02   3.7151+01   2.2585+02   1.6449+02   2.327 +00   7.8281+01
 50.0 TO 55.0   1.00000    6.2394+01    0.97510   1.5534+00   2.7148+02   4.1121+01   2.2422+02   1.8339+02   2.8923+00   9.2508+01
 55.0 TO 60.0   0.84162    7.267 +01    0.97301   1.961 +00   3.2776+02   4.7129+01   2.2171+02   2.1256+02   3.8857+00   1.1518+02
 60.0 TO 65.0   0.92148    8.165 +01    0.97549   2.0005+00   3.711 +02   5.1083+01   2.2002+02   2.3216+02   4.6356+00   1.3893+02
 65.0 TO 70.0   1.00000    9.1406+01    0.97754   2.0521+00   4.1707+02   5.5081+01   2.183 +02   2.5231+02   5.4782+00   1.6556+02
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SERIES
WITH GEARING
P(IC) = 16 HP
R(B) = .086 OHMS

ACCELERATION = 2.25 TO 3.25 MPH/SEC

15

PROBABILITY = 0.03580

VEHICLE SPEED MPH	PROBABILITY	POWER DEMAND HP	GEAR LOSS HP	TORQUE AT WHEEL FT-LB	MOTOR TORQUE FT-LB	MOTOR POWER HP	POWER INPUT KW	MOTOR EFFICIENCY	MOTOR LOSS KW	MOTOR CURRENT AMPS	TERMINAL VOLTAGE V
0.0 TO 5.0	0.00427	4.035+00	1.2859-01	6.0531+02	7.9953+01	4.163+00	7.9088+00	0.39260	4.8038+00	2.4655+02	3.2077+01
5.0 TO 10.0	0.00350	1.215+01	4.1011-01	6.076 +02	8.0403+01	1.256+01	1.1969+01	0.78262	2.6019+00	2.476 +02	4.8341+01
10.0 TO 15.0	0.00509	2.038+01	7.2642-01	6.1152+02	8.1069+01	2.111+01	1.8722+01	0.84082	2.98 +00	2.4915+02	7.5141+01
15.0 TO 20.0	0.00733	2.879+01	1.0808+00	6.1705+02	8.1952+01	2.987+01	2.5619+01	0.86960	3.3406+00	2.5122+02	1.0198+02
20.0 TO 25.0	0.00715	3.745+01	1.477 +00	6.2421+02	8.3055+01	3.892+01	3.2769+01	0.88587	3.7359+00	2.5379+02	1.2912+02
25.0 TO 30.0	0.00480	4.641+01	1.9192+00	6.3298+02	8.4377+01	4.833+01	4.022 +01	0.89620	4.1745+00	2.5688+02	1.5657+02
30.0 TO 35.0	0.00154	5.575+01	2.4123+00	6.4337+02	8.592 +01	5.817+01	4.7943+01	0.90478	4.5647+00	2.6048+02	1.8405+02
35.0 TO 40.0	0.00078	6.553+01	2.9615+00	6.5538+02	8.7685+01	6.849+01	5.6136+01	0.90993	5.0562+00	2.646 +02	2.1215+02
40.0 TO 45.0	0.00042	7.582+01	3.5726+00	6.6901+02	1.1956+02	7.939+01	6.5689+01	0.90127	6.4854+00	3.3898+02	1.9378+02
45.0 TO 50.0	0.00016	8.667+01	4.2519+00	6.8425+02	1.2251+02	9.092+01	7.4861+01	0.90570	7.0552+00	3.4587+02	2.1644+02
50.0 TO 55.0	0.00018	9.815+01	5.0063+00	7.0112+02	1.2576+02	1.031+02	8.4619+01	0.90911	7.651 +00	3.5346+02	2.394 +02
55.0 TO 60.0	0.00014	1.103+02	5.8431+00	7.156 +02	1.9398+02	1.161+02	9.8687+01	0.87789	1.205 +01	5.1263+02	1.9251+02
60.0 TO 65.0	0.00004	1.232+02	6.7703+00	7.397 +02	1.9977+02	1.3 +02	1.0985+02	0.88278	1.2877+01	5.2614+02	2.088 +02
65.0 TO 70.0	*00.00000	1.37 +02	7.7964+00	7.6142+02	2.0602+02	1.448+02	1.2186+02	0.88636	1.3647+01	5.4072+02	2.2537+02

VEHICLE SPEED MPH	ALPHA	PCU POWER KW	PCU EFFICIENCY	PCU LOSS KW	PCU INPUT CURRENT AMPS	BATTERY POWER KW	BATTERY VOLTAGE V	BATTERY CURRENT AMPS	BATTERY LOSS KW	RECTIFIER CURRENT AMPS
0.0 TO 5.0	0.15980	9.4265+00	0.83900	1.5176+00	3.94 +01	1.9815+00	2.3924+02	8.2823+00	5.8994-03	3.0965+01
5.0 TO 10.0	0.22898	1.3482+01	0.88781	1.5125+00	5.6698+01	6.037 +00	2.3778+02	2.5388+01	5.5435-02	3.1155+01
10.0 TO 15.0	0.34495	2.0224+01	0.92569	1.5028+00	8.5948+01	1.2779+01	2.3531+02	5.431 +01	2.5366-01	3.1482+01
15.0 TO 20.0	0.46378	2.7113+01	0.94489	1.4941+00	1.1651+02	1.9668+01	2.3271+02	8.4519+01	6.1434-01	3.1834+01
20.0 TO 25.0	0.58696	3.4256+01	0.95661	1.4863+00	1.4896+02	2.6811+01	2.2995+02	1.1659+02	1.169 +00	3.2216+01
25.0 TO 30.0	0.71509	4.1699+01	0.96453	1.4788+00	1.8369+02	3.4254+01	2.27 +02	1.5089+02	1.5581+00	3.2634+01
30.0 TO 35.0	0.84744	4.9414+01	0.97021	1.4717+00	2.2073+02	4.1969+01	2.2386+02	1.8748+02	3.0228+00	3.3093+01
35.0 TO 40.0	0.98765	5.76 +01	0.97457	1.4643+00	2.6133+02	5.0155+01	2.2041+02	2.2755+02	4.453 +00	3.361 +01
40.0 TO 45.0	0.90722	6.7427+01	0.97422	1.7382+00	3.0753+02	5.2872+01	2.1925+02	2.4114+02	5.0011+00	6.6308+01
45.0 TO 50.0	1.00000	7.6645+01	0.97672	1.784 +00	3.4587+02	5.8962+01	2.1658+02	2.7223+02	6.3734+00	7.9781+01
50.0 TO 55.0	1.00000	8.6626+01	0.97683	2.0065+00	3.5346+02	6.5353+01	2.1369+02	3.0582+02	8.0432+00	8.6751+01
55.0 TO 60.0	0.94341	1.0103+02	0.97673	2.351 +00	4.8362+02	7.5497+01	2.0892+02	3.6137+02	1.123 +01	1.2223+02
60.0 TO 65.0	1.00000	1.1232+02	0.97807	2.4621+00	5.2614+02	8.1753+01	2.0584+02	3.9716+02	1.3565+01	1.4309+02
65.0 TO 70.0	1.00000	1.2459+02	0.97810	2.728 +00	5.4072+02	8.8267+01	2.0251+02	4.3586+02	1.6337+01	1.5747+02

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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .066 OHMS

ACCELERATION =  3.25 TO  4.25 MPH/SEC

PROBABILITY =  0.02352

  VEHICLE    PROBABILITY  POWER       GEAR        TORQUE      MOTOR       MOTOR      POWER        MOTOR       MOTOR       MOTOR      TERMINAL
   SPEED                  DEMAND      LOSS       AT WHEEL     TORQUE      POWER      INPUT     EFFICIENCY     LOSS       CURRENT     VOLTAGE
    MPH                     HP         HP         FT-LB       FT-LB        HP         KW                       KW         AMPS          V

 0.0 TO  5.0    0.00365  5.341+00  1.7019-01  8.0117+02  1.0582+02  5.511+00  1.1183+01    0.36749  7.0734+00  3.0692+02  3.6437+01
 5.0 TO 10.0    0.00464  1.606+01  5.4229-01  8.0346+02  1.0632+02  1.661+01  1.6314+01    0.75927  3.9273+00  3.0808+02  5.2955+01
10.0 TO 15.0    0.00549  2.691+01  9.5909-01  8.0738+02  1.0793+02  2.787+01  2.5199+01    0.82478  4.4151+00  3.0974+02  8.1354+01
15.0 TO 20.0    0.00543  3.743+01  1.4236+00  8.1291+02  1.0796+02  3.935+01  3.4211+01    0.85792  4.8604+00  3.1192+02  1.0968+02
20.0 TO 25.0    0.00267  4.92 +01  1.9434+00  8.2007+02  1.0911+02  5.114+01  4.3416+01    0.87843  5.2776+00  3.146 +02  1.38  +02
25.0 TO 30.0    0.00118  6.078+01  2.5131+00  8.2684+02  1.1048+02  6.329+01  5.2848+01    0.89309  5.6496+00  3.178 +02  1.6629+02
30.0 TO 35.0    0.00056  7.273+01  3.1467+00  8.3923+02  1.1207+02  7.588+01  6.2671+01    0.90286  6.0872+00  3.2151+02  1.9492+02
35.0 TO 40.0    0.00018  8.512+01  3.8466+00  8.5124+02  1.1388+02  8.897+01  7.3007+01    0.90874  6.6621+00  3.2574+02  2.2412+02
40.0 TO 45.0    0.00002  9.801+01  4.6185+00  8.6497+02  1.5456+02  1.026+02  8.5553+01    0.89460  9.0169+00  4.2066+02  2.0338+02
45.0 TO 50.0    0.00002  1.114+02  5.469 +00  8.8011+02  1.5758+02  1.159+02  9.6968+01    0.89936  9.7584+00  4.2769+02  2.2672+02
50.0 TO 55.0    0.00006  1.255+02  6.4049+00  8.9698+02  1.609 +02  1.319+02  1.0874+02    0.90503  1.0326+01  4.3543+02  2.4974+02
55.0 TO 60.0 *00.00000  1.403+02  7.4336+00  9.1546+02  2.4676+02  1.478+02  1.2802+02    0.86091  1.7806+01  6.3582+02  2.0135+02
60.0 TO 65.0 *00.00000  1.559+02  8.563 +00  9.3556+02  2.5267+02  1.644+02  1.4167+02    0.86580  1.9012+01  6.4956+02  2.181 +02
65.0 TO 70.0 *00.00000  1.723+02  9.8017+00  9.5728+02  2.5902+02  1.821+02  1.5574+02    0.87196  1.9539+01  6.6438+02  2.3441+02

  VEHICLE        ALPHA      PCU         PCU         PCU      PCU INPUT    BATTERY     BATTERY     BATTERY     BATTERY    RECTIFIER
   SPEED                   POWER     EFFICIENCY     LOSS      CURRENT      POWER      VOLTAGE     CURRENT      LOSS       CURRENT
    MPH                     KW                       KW        AMPS         KW           V          AMPS        KW         AMPS

 0.0 TO  5.0    0.17710  1.2936+01     0.86450  1.7527+00  5.4356+01  5.491 +00  2.3797+02  2.3073+01  4.5785-02  3.113 +01
 5.0 TO 10.0    0.24825  1.8058+01     0.90343  1.7437+00  7.6481+01  1.0613+01  2.3611+02  4.495 +01  1.7376-01  3.1376+01
10.0 TO 15.0    0.37341  2.6925+01     0.93589  1.7259+00  1.1566+02  1.948 +01  2.3278+02  8.3681+01  6.0222-01  3.1824+01
15.0 TO 20.0    0.50220  3.5919+01     0.95242  1.7087+00  1.5664+02  2.8474+01  2.293 +02  1.2417+02  1.3261+00  3.2307+01
20.0 TO 25.0    0.63548  4.5108+01     0.96249  1.6919+00  1.9992+02  3.7663+01  2.2562+02  1.6692+02  2.3962+00  3.2833+01
25.0 TO 30.0    0.77379  5.4523+01     0.96927  1.675 +00  2.459 +02  4.7078+01  2.2172+02  2.1232+02  3.8772+00  3.3412+01
30.0 TO 35.0    0.91555  6.4328+01     0.97423  1.6571+00  2.9577+02  5.6883+01  2.1749+02  2.6154+02  5.8827+00  3.4062+01
35.0 TO 40.0    1.00000  7.4773+01     0.97638  1.766 +00  3.2574+02  6.7328+01  2.1278+02  3.1641+02  8.6099+00  3.2273+01
40.0 TO 45.0    0.99033  8.7535+01     0.97736  1.9818+00  4.1659+02  7.298 +01  2.1012+02  3.4732+02  1.0374+01  6.9189+01
45.0 TO 50.0    1.00000  9.9186+01     0.97763  2.2183+00  4.2769+02  8.1503+01  2.0596+02  3.9571+02  1.3466+01  7.6235+01
50.0 TO 55.0    1.00000  1.1122+02     0.97768  2.4815+00  4.3543+02  8.9954+01  2.0163+02  4.4613+02  1.7116+01  8.3234+01
55.0 TO 60.0    1.00000  1.3089+02     0.97807  2.8692+00  6.3582+02  1.0535+02  1.9307+02  5.4566+02  2.5605+01  1.2405+02
60.0 TO 65.0    1.00000  1.4465+02     0.97805  3.1791+00  6.4956+02  1.1428+02  1.8761+02  6.0915+02  3.1911+01  1.3698+02
65.0 TO 70.0    1.00000  1.5924+02     0.97801  3.5004+00  6.6438+02  1.2291+02  1.8187+02  6.7581+02  3.5278+01  1.5138+02
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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .086 OHMS

ACCELERATION =  4.25 TO  5.25 MPH/SEC

PROBABILITY =  0.01164

    VEHICLE     PROBABILITY  POWER       GEAR        TORQUE      MOTOR       MOTOR       POWER       MOTOR       MOTOR       MOTOR       TERMINAL
     SPEED                   DEMAND      LOSS       AT WHEEL     TORQUE      POWER       INPUT     EFFICIENCY    LOSS        CURRENT     VOLTAGE
      MPH                      HP         HP          FT-LB       FT-LB        HP          KW                     KW          AMPS          V

   0.0 TO  5.0   0.00191   6.646+00   2.118 -01   9.9702+02  1.3169+02   6.858+00   1.4477+01    0.35327   9.3629+00   3.6728+02   3.9417+01
   5.0 TO 10.0   0.00316   1.598+01   6.7448-01   9.9932+02  1.3223+02   2.066+01   2.0697+01    0.74438   5.2905+00   3.6855+02   5.6158+01
  10.0 TO 15.0   0.00330   3.344+01   1.1917+00   1.0032+03  1.3299+02   3.403+01   3.1841+01    0.81108   6.0151+00   3.7033+02   8.598 +01
  15.0 TO 20.0   0.00213   4.707+01   1.7669+00   1.0087+03  1.3397+02   4.884+01   4.3167+01    0.84374   6.7449+00   3.7261+02   1.1585+02
  20.0 TO 25.0   0.00109   6.095+01   2.4039+00   1.0159+03  1.3517+02   6.335+01   5.4145+01    0.87260   6.8578+00   3.7541+02   1.4423+02
  25.0 TO 30.0   0.00023   7.514+01   3.107 +00   1.0247+03  1.3659+02   7.825+01   6.5608+01    0.88940   7.2559+00   3.7871+02   1.7323+02
  30.0 TO 35.0   0.00002   8.97 +01   3.881 +00   1.035 +03  1.3823+02   9.358+01   7.7558+01    0.89582   7.7655+00   3.8254+02   2.0274+02
  35.0 TO 40.0 *00.00000   1.047+02   4.7317+00   1.0471+03  1.4009+02   1.094+02   9.0113+01    0.90563   8.5031+00   3.8688+02   2.3292+02
  40.0 TO 45.0 *00.00000   1.202+02   5.6645+00   1.0607+03  1.4157+02   1.258+02   1.0583+02    0.88690   1.157 +01   5.0233+02   2.1069+02
  45.0 TO 50.0 *00.00000   1.362+02   6.6861+00   1.0759+03  1.4265+02   1.429+02   1.1925+02    0.89404   1.2635+01   5.0952+02   2.3404+02
  50.0 TO 55.0 *00.00000   1.529+02   7.8035+00   1.0928+03  1.4603+02   1.608+02   1.336 +02    0.89747   1.3657+01   5.1741+02   2.5822+02
  55.0 TO 60.0 *00.00000   1.704+02   9.024 +00   1.1113+03  2.9958+02   1.794+02   1.5806+02    0.84649   2.4262+01   7.5902+02   2.0824+02
  60.0 TO 65.0 *00.00000   1.885+02   1.0355+01   1.1314+03  3.0557+02   1.989+02   1.7374+02    0.85375   2.5409+01   7.7299+02   2.2477+02
  65.0 TO 70.0 *00.00000   2.075+02   1.1807+01   1.1531+03  3.1202+02   2.193+02   1.9049+02    0.85872   2.6513+01   7.8803+02   2.4174+02

    VEHICLE       ALPHA       PCU        PCU          PCU       PCU INPUT    BATTERY     BATTERY     BATTERY     BATTERY     RECTIFIER
     SPEED                   POWER    EFFICIENCY      LOSS       CURRENT      POWER      VOLTAGE     CURRENT      LOSS        CURRENT
      MPH                     KW                       KW         AMPS          KW          V          AMPS         KW          AMPS

   0.0 TO  5.0   0.18950   1.6474+01    0.87677   1.9972+00   6.9601+01   9.0296+00   2.3669+02   3.8148+01   1.2515-01   3.1298+01
   5.0 TO 10.0   0.26255   2.268 +01    0.91256   1.9831+00   9.6763+01   1.5235+01   2.3439+02   6.5    +01   3.6335-01   3.1606+01
  10.0 TO 15.0   0.39654   3.3795+01    0.94216   1.9546+00   1.4685+02   2.635 +01   2.3013+02   1.145 +02   1.1274+00   3.219 +01
  15.0 TO 20.0   0.53634   4.5092+01    0.95729   1.9258+00   1.9984+02   3.7647+01   2.2563+02   1.6685+02   2.3942+00   3.2832+01
  20.0 TO 25.0   0.67526   5.6043+01    0.96612   1.8982+00   2.5349+02   4.8598+01   2.2107+02   2.1982+02   4.1556+00   3.3509+01
  25.0 TO 30.0   0.82481   6.7476+01    0.97230   1.8685+00   3.1226+02   6.0031+01   2.1609+02   2.778 +02   6.637 +00   3.4282+01
  30.0 TO 35.0   0.98543   7.9394+01    0.97687   1.8358+00   3.7698+02   7.1949+01   2.106 +02   3.4163+02   1.0037+01   3.5176+01
  35.0 TO 40.0   1.00000   9.221 +01    0.97726   2.0968+00   3.8680+02   8.4765+01   2.0432+02   4.1486+02   1.4801+01   3.1082+01
  40.0 TO 45.0   1.00000   1.0821+02    0.97801   2.3788+00   5.0233+02   9.3663+01   1.9965+02   4.6912+02   1.8926+01   6.7485+01
  45.0 TO 50.0   1.00000   1.2192+02    0.97803   2.6776+00   5.0952+02   1.0424+02   1.9372+02   5.3813+02   2.4903+01   7.388 +01
  50.0 TO 55.0   1.00000   1.366 +02    0.97805   2.997 +00   5.1741+02   1.1533+02   1.8694+02   6.1693+02   3.2731+01   8.0531+01
  55.0 TO 60.0   1.00000   1.6167+02    0.97767   3.6096+00   7.5902+02   1.3612+02   1.7189+02   7.9155+02   5.3937+01   1.1989+02
  60.0 TO 65.0   1.00000   1.7772+02    0.97760   3.9804+00   7.7299+02   1.4716+02   1.6176+02   9.0974+02   7.1176+01   1.3285+02
  65.0 TO 70.0   1.00000   1.9487+02    0.97752   4.3756+00   7.8803+02   1.5855+02   1.4764+02   1.0738+03   9.5177+01   1.4672+02
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SERIES
WITH GEARING
P(IC) = 16 HP
R(B) = .086 OHMS

ACCELERATION = 5.25 TO 6.25 MPH/SEC

PROBABILITY = 0.00484

VEHICLE SPEED MPH	PROBABILITY	POWER DEMAND HP	GEAR LOSS HP	TORQUE AT WHEEL FT-LB	MOTOR TORQUE FT-LB	MOTOR POWER HP	POWER INPUT KW	MOTOR EFFICIENCY	MOTOR LOSS KW	MOTOR CURRENT AMPS	TERMINAL VOLTAGE V
0.0 TO 5.0	0.00046	7.952+00	2.5341-01	1.1928+03	1.5756+02	8.205+00	1.6518+01	0.37044	1.0359+01	4.2765+02	3.8626+01
5.0 TO 10.0	0.00196	2.39 +01	6.0668-01	1.1551+03	1.5815+02	2.471+01	2.5607+01	0.71957	7.181 +00	4.2903+02	5.9687+01
10.0 TO 15.0	0.00143	3.996+01	1.4244+00	1.1991+03	1.5896+02	4.139+01	3.8785+01	0.79584	7.9182+00	4.3091+02	9.0009+01
15.0 TO 20.0	0.00078	5.621+01	2.1099+00	1.2046+03	1.5999+02	5.832+01	5.2058+01	0.83548	8.5644+00	4.3331+02	1.2014+02
20.0 TO 25.0	0.00021	7.27 +01	2.8673+00	1.2117+03	1.6123+02	7.557+01	6.5331+01	0.86260	8.9759+00	4.3621+02	1.4977+02
25.0 TO 30.0	+00.00000	8.95 +01	3.7008+00	1.2205+03	1.627 +02	9.32 +01	7.8984+01	0.87999	9.4786+00	4.3963+02	1.7965+02
30.0 TO 35.0	+00.00000	1.066+02	4.6154+00	1.2309+03	1.6438+02	1.112+02	9.2903+01	0.89333	9.9051+00	4.4357+02	2.0944+02
35.0 TO 40.0	+00.00000	1.242+02	5.6160+00	1.2429+03	1.6629+02	1.299+02	1.0749+02	0.90117	1.0623+01	4.4802+02	2.3993+02
40.0 TO 45.0	+00.00000	1.424+02	6.7104+00	1.2565+03	2.2457+02	1.491+02	1.2686+02	0.87654	1.5661+01	5.8401+02	2.1722+02
45.0 TO 50.0	+00.00000	1.61 +02	7.9032+00	1.2718+03	2.2772+02	1.67 +02	1.4255+02	0.88407	1.6525+01	5.9135+02	2.4106+02
50.0 TO 55.0	+00.00000	1.804+02	9.202 +00	1.2886+03	2.3117+02	1.896+02	1.5874+02	0.89074	1.7343+01	5.9939+02	2.6484+02
55.0 TO 60.0	+00.00000	2.004+02	1.0614+01	1.3071+03	3.5238+02	2.11 +02	1.8951+02	0.83041	3.2138+01	8.8221+02	2.1482+02
60.0 TO 65.0	+00.00000	2.212+02	1.2148+01	1.3272+03	3.5847+02	2.333+02	2.0782+02	0.83731	3.381 +01	8.9641+02	2.3184+02
65.0 TO 70.0	+00.00000	2.428+02	1.3812+01	1.349 +03	3.6501+02	2.566+02	2.2616+02	0.84615	3.4793+01	9.1168+02	2.4807+02

VEHICLE SPEED MPH	ALPHA	PCU POWER KW	PCU EFFICIENCY	PCU LOSS KW	PCU INPUT CURRENT AMPS	BATTERY POWER KW	BATTERY VOLTAGE V	BATTERY CURRENT AMPS	BATTERY LOSS KW	RECTIFIER CURRENT AMPS
0.0 TO 5.0	0.18614	1.8774+01	0.87983	2.2559+00	7.9603+01	1.1329+01	2.3584+02	4.8036+01	1.9844-01	3.1411+01
5.0 TO 10.0	0.27914	2.7837+01	0.91990	2.2294+00	1.1976+02	2.0392+01	2.3243+02	8.773 +01	6.619 -01	3.1871+01
10.0 TO 15.0	0.41833	4.0974+01	0.94659	2.1883+00	1.8926+02	3.3529+01	2.2729+02	1.4751+02	1.8713+00	3.2592+01
15.0 TO 20.0	0.56384	5.4204+01	0.96040	2.1462+00	2.4431+02	4.6759+01	2.2185+02	2.1076+02	3.8201+00	3.3391+01
20.0 TO 25.0	0.71532	6.7434+01	0.96881	2.1026+00	3.1204+02	5.9989+01	2.1611+02	2.7759+02	6.6266+00	3.4279+01
25.0 TO 30.0	0.87853	8.1039+01	0.97463	2.0553+00	3.8623+02	7.3594+01	2.0982+02	3.5075+02	1.058 +01	3.5307+01
30.0 TO 35.0	1.00000	9.5018+01	0.97774	2.1146+00	4.4357+02	8.7573+01	2.0287+02	4.3166+02	1.6024+01	3.4583+01
35.0 TO 40.0	1.00000	1.0994+02	0.97777	2.4438+00	4.4802+02	1.0249+02	1.9473+02	5.2634+02	2.3825+01	3.0189+01
40.0 TO 45.0	1.00000	1.2969+02	0.97813	2.8365+00	5.8401+02	1.1514+02	1.8706+02	6.1554+02	3.2584+01	6.5463+01
45.0 TO 50.0	1.00000	1.4573+02	0.97812	3.1875+00	5.9135+02	1.2805+02	1.782 +02	7.186 +02	4.4409+01	7.1737+01
50.0 TO 55.0	1.00000	1.6229+02	0.97812	3.5503+00	5.9939+02	1.4101+02	1.6766+02	8.4106+02	6.0835+01	7.8523+01
55.0 TO 60.0	1.00000	1.9399+02	0.97693	4.4737+00	8.8221+02	1.6845+02	0. +00	0. +00	0. +00	1.1613+02
60.0 TO 65.0	0.00000	2.0782+02	1.00000	0. +00	0. +00	1.7726+02	0. +00	0. +00	0. +00	0. +00
65.0 TO 70.0	0.00000	2.2616+02	1.00000	0. +00	0. +00	1.8984+02	0. +00	0. +00	0. +00	0. +00

SERIES
WITH GEARING
P(IC) = 16 HP
R(B) = .086 OHMS

ACCELERATION = 7.25 TO 8.25 MPH/SEC

PROBABILITY = 0.00030

VEHICLE SPEED MPH	PROBABILITY	POWER DEMAND HP	GEAR LOSS HP	TORQUE AT WHEEL FT-LB	MOTOR TORQUE FT-LB	MOTOR POWER HP	POWER INPUT KW	MOTOR EFFICIENCY	MOTOR LOSS KW	MOTOR CURRENT AMPS	TERMINAL VOLTAGE V
0.0 TO 5.0	0.00034	1.056+01	3.3663-01	1.5846+03	2.093 +02	1.09 +01	2.2038+01	0.36783	1.3969+01	5.4837+02	4.0298+01
5.0 TO 10.0	0.00010	3.173+01	1.071 +00	1.5869+03	2.0959+02	3.28 +01	3.6005+01	0.67950	1.1539+01	5.4997+02	6.5467+01
10.0 TO 15.0	0.00012	5.302+01	1.8897+00	1.5908+03	2.1089+02	5.431+01	5.3474+01	0.76582	1.2522+01	5.5208+02	9.6859+01
15.0 TO 20.0	0.00004	7.449+01	2.7961+00	1.5963+03	2.1231+02	7.729+01	7.0723+01	0.81495	1.3086+01	5.547 +02	1.2749+02
20.0 TO 25.0	*00.00000	9.621+01	3.7941+00	1.6035+03	2.1335+02	1. +02	8.6144+01	0.84603	1.357 +01	5.5783+02	1.5801+02
25.0 TO 30.0	*00.00000	1.182+02	4.8886+00	1.6122+03	2.1491+02	1.231+02	1.0588+02	0.86709	1.4072+01	5.6147+02	1.8858+02
30.0 TO 35.0	*00.00000	1.406+02	6.0842+00	1.6226+03	2.167 +02	1.467+02	1.2424+02	0.88059	1.4835+01	5.6563+02	2.1965+02
35.0 TO 40.0	*00.00000	1.634+02	7.3869+00	1.6346+03	2.187 +02	1.798+02	1.4318+02	0.88978	1.5782+01	5.7031+02	2.5107+02
40.0 TO 45.0	*00.00000	1.868+02	8.8023+00	1.6483+03	2.9458+02	1.956+02	1.697 +02	0.85954	2.3836+01	7.4735+02	2.2707+02
45.0 TO 50.0	*00.00000	2.137+02	1.0337+01	1.6635+03	2.9786+02	2.21 +02	1.8983+02	0.86834	2.4553+01	7.55 +02	2.5143+02
50.0 TO 55.0	*00.00000	2.352+02	1.1999+01	1.6804+03	3.0144+02	2.472+02	2.1019+02	0.87716	2.582 +01	7.6334+02	2.7537+02
55.0 TO 60.0	*00.00000	2.605+02	1.3794+01	1.6988+03	4.5798+02	2.742+02	2.4828+02	0.82382	4.3741+01	1.1286+03	2.1999+02
60.0 TO 65.0	*00.00000	2.865+02	1.5733+01	1.7189+03	4.6426+02	3.022+02	2.7059+02	0.83289	4.5219+01	1.1432+03	2.3668+02
65.0 TO 70.0	*00.00000	3.133+02	1.7823+01	1.7407+03	4.71 +02	3.311+02	2.9271+02	0.84364	4.5765+01	1.1589+03	2.5255+02

VEHICLE SPEED MPH	ALPHA	PCU POWER KW	PCU EFFICIENCY	PCU LOSS KW	PCU INPUT CURRENT AMPS	BATTERY POWER KW	BATTERY VOLTAGE V	BATTERY CURRENT AMPS	BATTERY LOSS KW	RECTIFIER CURRENT AMPS
0.0 TO 5.0	0.19442	2.4901+01	0.88742	2.8032+00	1.0661+02	1.7458+01	[illegible]	7.4742+01	4.8043-01	3.1719+01
5.0 TO 10.0	0.30878	3.8751+01	0.92912	2.7465+00	1.6982+02	3.1306+01	2.2818+02	1.3719+02	1.6188+00	3.2465+01
10.0 TO 15.0	0.46008	5.6144+01	0.95243	2.6703+00	2.54 +02	4.8899+01	2.2183+02	2.2032+02	4.1345+00	3.3516+01
15.0 TO 20.0	0.61922	7.3314+01	0.96466	2.5905+00	3.4348+02	6.5869+01	2.1364+02	3.084 +02	8.1901+00	3.4708+01
20.0 TO 25.0	0.79231	9.0646+01	0.97238	2.5029+00	4.4197+02	8.3201+01	2.0529+02	4.5567+02	1.4152+01	3.6121+01
25.0 TO 30.0	0.98572	1.0828+02	0.97780	2.403 +00	5.5345+02	1.0084+02	1.9565+02	5.154 +02	2.2044+01	3.7863+01
30.0 TO 35.0	1.00000	1.2701+02	0.97812	2.7781+00	5.6563+02	1.1957+02	1.8438+02	6.4929+02	3.6255+01	3.2989+01
35.0 TO 40.0	1.00000	1.4638+02	0.97812	3.2016+00	5.7031+02	1.3898+02	1.695 +02	8.1971+02	5.7785+01	2.8861+01
40.0 TO 45.0	1.00000	1.7356+02	0.97772	3.866 +00	7.4735+02	1.5981+02	1.4692+02	1.0823+03	1.0073+02	6.2599+01
45.0 TO 50.0	0.00000	1.8983+02	1.00000	0. +00	0. +00	1.7214+02	0. +00	0. +00	0. +00	0. +00
50.0 TO 55.0	0.00000	2.1019+02	1.00000	0. +00	0. +00	1.8892+02	0. +00	0. +00	0. +00	0. +00
55.0 TO 60.0	0.00000	2.4828+02	1.00000	0. +00	0. +00	2.2274+02	0. +00	0. +00	0. +00	0. +00
60.0 TO 65.0	0.00000	2.7059+02	1.00000	0. +00	0. +00	2.4002+02	0. +00	0. +00	0. +00	0. +00
65.0 TO 70.0	0.00000	2.9271+02	1.00000	0. +00	0. +00	2.5638+02	0. +00	0. +00	0. +00	0. +00

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SERIES
WITH GEARING
P(IC) =  16 HP
R(B) =  .C86 CHMS

ACCELERATICN =  C.25 TC  7.25 MPH/SEC                                                                              20

PROBABILITY =  C.CC157

  VEHICLE     PROBABILITY  POWER      GEAR        TORQUE      MOTOR       MOTOR       POWER        MOTOR      MCTOR       MOTOR       TERMINAL
   SPEED                   DEMAND     LOSS        AT WHEEL    TORQUE      POWER       INPUT      EFFICIENCY    LCSS       CURRENT     VOLTAGE
    MPH                      HP        HP          FT-LB       FT-LB        HP          KW                     KW         AMPS          V


  0.C TO  5.0    C.C0012  9.253+00  2.9502-01  1.3687+03  1.8343+02  9.553+00  1.7621+01   0.40427  1.0457+01  4.8801+02  3.6108+01
  5.0 TO 10.C    C.CCC65  2.732+01  9.3388-01  1.391 +03  1.8407+02  2.875+01  3.0579+01   C.7C131  9.1336+C0  4.895 +02  6.2471+01
 10.0 TC 15.C    C.CC051  4.047+01  1.657 +00  1.3949+03  1.8492+02  4.815+01  4.5905+01   0.78225  9.9557+00  4.915 +02  9.3399+01
 15.0 TO 20.0    0.CCC25  6.535+01  2.453 +00  1.4004+03  1.86  +02  6.78 +01  6.1187+01   0.82640  1.0621+01  4.94  +02  1.2386+02
 20.0 TO 25.0 *00.C0C00  8.445+01  3.3308+00  1.4076+03  1.8729+02  8.778+01  7.6569+01   0.85497  1.1104+01  4.9702+02  1.5405+02
 25.0 TO 30.0 *0C.C0000  1.038+02  4.2946+00  1.4164+03  1.888 +02  1.081+02  9.2147+01   0.87532  1.1468+01  5.0055+02  1.8409+02
 30.0 TO 35.0 *CC.C00C0  1.236+02  5.3498+00  1.4268+03  1.9054+02  1.29  +02  1.0832+02   C.88806  1.2125+01  5.046 +02  2.1467+02
 35.0 TO 40.0 *CC.CC0C0  1.438+02  6.5017+00  1.4388+03  1.925 +02  1.503+02  1.2516+02   0.89595  1.3C22+01  5.0917+02  2.4582+02
 40.0 TO 45.0 *00.C0000  1.646+02  7.7563+00  1.4524+03  2.5958+02  1.723+02  1.4843+02   C.86594  1.9898+01  6.6568+02  2.2297+02
 45.0 TO 50.0 *CC.C0CC0  1.859+02  9.1203+00  1.4676+03  2.6279+02  1.95  +02  1.6583+02   0.87699  2.0397+01  6.7317+02  2.4634+02
 50.0 TO 55.0 *0C.C0C00  2.078+02  1.06  +01  1.4845+C3  2.663 +02  2.134+02  1.8402+02   0.88516  2.1131+01  6.8137+02  2.7008+02
 55.0 TO 60.0 *0C.C00C0  2.304+02  1.2204+01  1.503 +03  4.0518+02  2.426+02  2.1965+02   0.82382  3.8659+01  1.0054+03  2.1847+02
 60.0 TO 65.0 *0C.CCC00  2.538+02  1.394 +01  1.5231+03  4.1136+02  2.678+02  2.3976+02   0.83289  4.CC66+01  1.0198+03  2.351 +02
 65.0 TO 70.0 *0C.CCC00  2.78 +02  1.5817+01  1.5448+03  4.1801+02  2.938+02  2.5977+02   0.84364  4.0616+01  1.0353+03  2.509 +02

  VEHICLE       ALPHA      PCU         PCU         PCU        PCU INPUT   BATTERY     BATTERY     BATTERY     BATTERY     RECTIFIER
   SPEED                   POWER    EFFICIENCY     LOSS       CURRENT     POWER       VOLTAGE     CURRENT     LOSS        CURRENT
    MPH                     KW                      KW         AMPS        KW           V          AMPS        KW          AMPS


  0.0 TO  5.0   0.17546  2.0151+01   0.87443  2.5302+00  8.5629+01  1.2706+01  2.3533+02  5.3993+01  2.5071-01  3.1479+01
  5.0 TO 10.0   0.29314  3.3064+01   0.92486  2.4843+00  1.4349+02  2.5619+01  2.3042+02  1.1118+02  1.C631+00  3.2151+01
 10.0 TO 15.0   0.43840  4.8332+01   0.94977  2.4274+00  2.1547+02  4.0887+01  2.243 +02  1.8228+02  2.8576+00  3.3027+01
 15.0 TO 20.0   C.59061  6.3555+01   0.96273  2.3684+00  2.9176+02  5.611 +01  2.1783+02  2.5759+02  5.7061+00  3.4009+01
 20.0 TO 25.0   C.75264  7.8874+01   0.97077  2.3054+00  3.7408+02  7.1429+01  2.1085+02  3.3877+02  9.8698+00  3.5135+01
 25.0 TO 30.0   C.92801  9.4383+01   0.97630  2.2361+00  4.6452+02  8.6938+01  2.0318+02  4.2787+02  1.5744+01  3.646 +01
 30.0 TO 35.0   1.C0000  1.1075+02   0.97802  2.4338+00  5.046 +02  1.0331+02  1.9426+02  5.3183+02  2.4324+01  3.375 +01
 35.0 TO 40.0   1.00000  1.2797+02   0.97803  2.8105+00  5.0917+02  1.2052+02  1.8351+02  6.5677+02  3.7C96+01  2.9475+01
 40.0 TO 45.0   1.C0000  1.5176+02   0.97801  3.3365+00  6.6568+02  1.3721+02  1.7C98+02  8.0249+02  5.5382+01  6.3767+01
 45.0 TO 50.0   1.C0000  1.6956+02   0.97799  3.7311+00  6.7317+02  1.5187+02  1.5658+02  9.6993+02  8.0906+01  7.019 +01
 50.0 TO 55.0   1.00000  1.8816+02   0.97797  4.145 +00  6.8137+02  1.6689+02  1.2686+02  1.3154+03  1.4882+02  7.6989+01
 55.0 TO 60.0   0.00000  2.1965+02   1.00000  0.     +00  0.     +00  1.9411+02  0.     +00  0.     +00  0.     +00  0.     +00
 60.0 TO 65.0   C.00000  2.3976+02   1.00000  0.     +00  0.     +00  2.0919+02  0.     +00  0.     +0C  0.     +00  0.     +00
 65.0 TO 70.0   0.00000  2.5977+02   1.00000  0.     +00  0.     +00  2.2344+02  0.     +00  0.     +00  0.     +00  0.     +00
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PARALLEL ENT Run TAA
WITH GEARING
P(IC) = 11.75 HP
R(B) = .086 OHMS
ETA(GC) = .900

1

ANY ACCELERATION

VEHICLE SPEED MPH N_R	SPEEDER INPUT POWER KW P_{A1}	SPEEDER VOLTAGE V_A	SPEEDER EFFICIENCY η_A	SPEEDER CURRENT AMPS I_A	η_{PCUA} EFFICIENCY	P_{PCUA} POWER OUT KW	DRIVE SHAFT POWER HP P_o	G1 EFFICIENCY η_{G1}	η_{gM}
0.0 TO 5.0	7.4682+00	1.8941+02	0.85151	3.3574+01	0.96760	6.1533+00	5.5585-01	0.96911	0.98889
5.0 TO 10.0	6.6333+00	1.6823+02	0.84461	3.3302+01	0.96349	5.398 +00	1.6795+00	0.96735	0.98709
10.0 TO 15.0	5.7583+00	1.4705+02	0.83524	3.2932+01	0.95618	4.6405+00	2.7992+00	0.96556	0.98529
15.0 TO 20.0	4.9634+00	1.2588+02	0.82200	3.241 +01	0.95106	3.8802+00	3.9189+00	0.96382	0.98349
20.0 TO 25.0	4.1284+00	1.047 +02	0.80076	3.1573+01	0.94097	3.1107+00	5.0386+00	0.96205	0.98169
25.0 TO 30.0	3.2934+00	8.3529+01	0.77401	3.0518+01	0.92567	2.3597+00	6.1583+00	0.96029	0.97989
30.0 TO 35.0	2.4585+00	6.2353+01	0.71529	2.8203+01	0.89924	1.5813+00	7.278 +00	0.95852	0.97809
35.0 TO 40.0	1.6235+00	4.1176+01	0.53388	2.105 +01	0.83779	7.2618-01	8.3977+00	0.95676	0.97629
40.0 TO 45.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	1.5165+01	0.95500	0.97449
45.0 TO 50.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	1.8966+01	0.95323	0.97268
50.0 TO 55.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	2.3433+01	0.95147	0.97088
55.0 TO 60.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	2.8637+01	0.94970	0.96908
60.0 TO 65.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	3.4649+01	0.94794	0.96728
65.0 TO 70.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	4.154 +01	0.94617	0.96548
70.0 TO 75.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	4.9382+01	0.94441	0.96368
75.0 TO 80.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	5.8249+01	0.94264	0.96188
80.0 TO 85.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	6.8213+01	0.94088	0.96008
85.0 TO 90.0	0. +00	0. +00	0.53388	0. +00	0.00000	0. +00	7.9349+01	0.93911	0.95828

```
PARALLEL EHT  Run TAA
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .C86 OHMS
ETA(GO) =  .900                                                                                              2

ACCELERATION = -8.25 TO -7.25 MPH/SEC

     VEHICLE       TORQUE        MOTOR         MOTOR        POWER        MOTOR       TERMINAL
      SPEED      AT WHEEL       TORQUE         POWER        INPUT     EFFICIENCY     VOLTAGE
       MPH         FT-LB         FT-LB          HP            KW
        WR          TR            TM            PMo          PMI           nM           VM

    0.0 TO  5.0 -1.4512+C3 -1.23C7+02 -9.9246+C0 -3.8603+00     0.52160  7.9336+00
    5.0 TO 10.0 -1.4465+03 -1.2267+02 -2.9678+01 -1.7332+01     0.78315  3.5703+01
   10.0 TO 15.0 -1.4449+03 -1.2215+02 -4.9252+01 -3.1131+01     0.84762  6.4347+01
   15.0 TO 20.0 -1.4394+03 -1.215 +02 -6.8585+01 -4.457 +01     0.87929  9.3365+01
   20.0 TO 25.0 -1.4323+C3 -1.2072+02 -8.7615+01 -5.8669+01     0.89797  1.2245+02
   25.0 TO 30.0 -1.4235+03 -1.1981+02 -1.0628+02 -7.207 +01     0.90934  1.5136+02
   30.0 TO 35.0 -1.4131+C3 -1.1878+02 -1.2452+02 -8.4473+01     0.90969  1.7867+02
   35.0 TO 40.0 -1.4011+03 -1.1763+02 -1.4228+02 -9.6547+01     0.90995  2.0586+02
   40.0 TO 45.0 -1.3875+03 -1.6051+02 -1.6503+02 -1.1122+02     0.90379  1.8697+02
   45.0 TO 50.0 -1.3722+03 -1.6036+02 -1.8427+02 -1.2419+C2     0.90379  2.0892+02
   50.0 TO 55.0 -1.3554+03 -1.6023+02 -2.0351+02 -1.3715+02     0.90379  2.3087+02
   55.0 TO 60.0 -1.3369+03 -2.4019+02 -2.2274+02 -1.5012+02     0.90379  1.8301+02
   60.0 TO 65.0 -1.3168+03 -2.40C7+02 -2.4199+02 -1.6309+02     0.90379  1.989 +02
   65.0 TO 70.0 -1.295 +03 -2.4    +02 -2.6128+02 -1.7609+02     0.90379  2.148 +02

     VEHICLE         ALPHA    PPCUM INPUT     nPCUM     IPCUM INPUT   BATTERY      BATTERY     BATTERY      BATTERY
      SPEED            a         POWER     EFFICIENCY     CURRENT      POWER       VOLTAGE     CURRENT       LOSS
       MPH                        KW                       AMPS          KW                       AMPS         KW
                                                                         PB           VB           IB          ΔPB

    0.0 TO  5.0     0.98283 -2.0289+00      0.52560 -8.3526+C0 -8.1823+00  2.4291+02 -3.3683+01  9.7574-C2
    5.0 TO 10.0     0.87111 -1.547 +01      0.89258 -6.2566+01 -2.0868+01  2.4726+02 -8.4397+01  6.1257-C1
   10.0 TO 15.0     0.75576 -2.924 +01      0.93926 -1.1622+02 -3.388 +01  2.5158+02 -1.3466+02  1.5596+C0
   15.0 TO 20.0     C.65054 -4.3053+01      0.95736 -1.6831+02 -4.6933+01  2.5578+02 -1.8349+02  2.8955+0C
   20.0 TO 25.0     0.54427 -5.6727+01      0.96690 -2.1834+02 -5.9838+01  2.5981+02 -2.3031+02  4.5618+00
   25.0 TO 30.0     0.44153 -7.0166+C1      0.97275 -2.6591+02 -7.2465+01  2.6364+02 -2.7486+02  6.4973+0C
   30.0 TO 35.0     0.34668 -8.2491+01      0.97654 -3.0887+02 -8.4072+01  2.6708+02 -3.1479+02  8.5219+00
   35.0 TO 40.0     0.25418 -9.4551+01      0.97931 -3.4578+02 -9.5277+01  2.7031+02 -3.5247+02  1.0684+01
   40.0 TO 45.0     0.33222 -1.0891+02      0.97919 -3.9725+02 -1.0891+02  2.7417+02 -3.9725+02  1.3571+01
   45.0 TO 50.0     0.26154 -1.2185+02      0.98113 -4.3874+02 -1.2185+02  2.7773+02 -4.3874+02  1.6554+01
   50.0 TO 55.0     0.19320 -1.3478+02      0.98271 -4.7929+02 -1.3478+02  2.8122+02 -4.7929+02  1.5755+01
   55.0 TO 60.0     0.36910 -1.4723+02      0.98078 -5.1751+02 -1.4723+02  2.8451+02 -5.1751+02  2.3032+01
   60.0 TO 65.0     0.32136 -1.6017+02      0.98210 -5.5645+02 -1.6017+02  2.8786+02 -5.5645+02  2.6629+01
   65.0 TO 70.0     0.27455 -1.7313+02      0.98324 -5.9468+02 -1.7313+02  2.9115+02 -5.9468+02  3.0413+01
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```
PARALLEL EPT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GC) =  .900

ACCELERATION = -7.25 TC -6.25 MPH/SEC


  VEHICLE      TORQUE       MOTOR       MOTOR       POWER       MOTOR     TERMINAL
   SPEED      AT WHEEL      TORQUE      POWER       INPUT     EFFICIENCY   VOLTAGE
    MPH        FT-LB        FT-LB        HP          KW                       V


  0.0 TO  5.0 -1.2553+C3 -1.0738+02 -8.6592+00 -3.5199+00    0.54512   8.0833+00
  5.0 TO 10.0 -1.253 +03 -1.0701+02 -2.5888+01 -1.5345+01    0.79489   3.5338+01
 10.0 TU 15.0 -1.2491+03 -1.0651+02 -4.2948+01 -2.736 +01    0.85429   6.324 +01
 15.0 TO 20.0 -1.2436+03 -1.0589+02 -5.9775+01 -3.9366+01    0.88314   9.1423+01
 20.0 TO 25.0 -1.2364+03 -1.0514+02 -7.631 +01 -5.1236+01    0.90039   1.1967+02
 25.0 TO 30.0 -1.2276+03 -1.0426+02 -9.249 +01 -6.2949+01    0.91271   1.4802+02
 30.0 TO 35.0 -1.2172+03 -1.0326+02 -1.0825+02 -7.3713+01    0.91313   1.7469+02
 35.0 TO 40.0 -1.2C52+03 -1.0213+02 -1.2354+02 -8.4149+01    0.91338   2.012 +02
 40.0 TO 45.0 -1.1516+C3 -1.3989+02 -1.4383+02 -9.7123+01    0.90549   1.8159+02
 45.0 TO 50.0 -1.1764+03 -1.3978+02 -1.6062+02 -1.0846+02    0.90551   2.0292+02
 50.0 TO 55.0 -1.1595+C3 -1.3569+02 -1.7742+02 -1.198 +02    0.90553   2.2425+02
 55.0 TO 60.0 -1.141 +C3 -2.0944+02 -1.9422+02 -1.309 +02    0.90379   1.7502+02
 60.0 TO 65.0 -1.12C9+03 -2.0938+02 -2.1105+02 -1.4224+02    0.90379   1.9021+02
 65.0 TO 70.0 -1.0992+03 -2.0936+02 -2.2792+02 -1.536 +02    0.90379   2.0542+02

  VEHICLE       ALPHA   PPCUM INPUT    ηPCUM     PCUT INPUT   BATTERY    BATTERY    BATTERY    BATTERY
   SPEED                   POWER    EFFICIENCY    CURRENT      POWER     VOLTAGE    CURRENT     LOSS
    MPH                     KW                     AMPS         KW          V        AMPS        KW


  0.0 TO  5.0    0.98300 -1.7976+00    0.51069 -7.4028+00 -7.9509+00 2.4282+02 -3.2742+01  9.22  -02
  5.0 TO 10.0    0.87302 -1.3599+01    0.88618 -5.5139+01 -1.8997+01 2.4662+02 -7.7026+01  5.1C24-01
 10.0 TO 15.0    0.76376 -2.559 +01    0.93532 -1.022 +02 -3.023 +01 2.5038+02 -1.2C73+02  1.2536+00
 15.0 TO 20.0    0.65649 -3.7575+01    0.95450 -1.4791+02 -4.1455+01 2.5403+02 -1.6318+02  2.2901+00
 20.0 TU 25.0    0.55175 -4.9426+01    0.96467 -1.9191+02 -5.2537+01 2.5755+02 -2.0399+02  3.5786+00
 25.0 TO 30.0    0.44916 -6.1122+01    0.97097 -2.3425+02 -6.3482+01 2.6093+02 -2.4329+02  5.0506+00
 30.0 TO 35.0    0.35466 -7.1873+01    0.97503 -2.7231+02 -7.3454+01 2.6394+02 -2.783 +02  6.6608+00
 35.0 TU 40.0    0.26236 -8.2297+01    0.97800 -3.085 +02 -8.3023+01 2.6677+02 -3.1122+02  8.3298+00
 40.0 TO 45.0    0.34284 -9.4575+01    0.97788 -3.5147+02 -9.4975+01 2.7023+02 -3.5147+02  1.0623+01
 45.0 TO 50.0    0.27272 -1.0629+02    0.97997 -3.8873+02 -1.0629+02 2.7343+02 -3.8873+02  1.2995+01
 50.0 TO 55.0    0.20403 -1.176 +02    0.98166 -4.2524+02 -1.176 +02 2.7657+02 -4.2524+02  1.5551+01
 55.0 TO 60.0    0.38654 -1.2821+02    0.97946 -4.5879+02 -1.2821+02 2.7946+02 -4.5879+02  1.8101+01
 60.0 TO 65.0    0.33947 -1.3952+02    0.98090 -4.9393+02 -1.3952+02 2.8248+02 -4.9393+02  2.0981+01
 65.0 TO 70.0    0.29321 -1.5086+02    0.98212 -5.2851+02 -1.5086+02 2.8545+02 -5.2851+02  2.4021+01
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```
PARALLEL EHT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GC) =  .900

ACCELERATION = -6.25 TO -5.25 MPH/SEC


  VEHICLE      TORQUE      MOTOR       MOTOR       POWER      MOTOR     TERMINAL
   SPEED     AT WHEEL      TORQUE      POWER       INPUT    EFFICIENCY   VOLTAGE
    MPH        FT-LB       FT-LB        HP          KW                      V


  0.0 TO  5.0 -1.0554+03 -9.1689+01 -7.3938+00 -3.0503+00    0.56050  8.0563+00
  5.0 TO 10.0 -1.0571+03 -9.135 +01 -2.2099+01 -1.3248+01    0.80392  3.4639+01
 10.0 TO 15.0 -1.0532+03 -9.0883+01 -3.6644+01 -2.3476+01    0.85912  6.163 +01
 15.0 TO 20.0 -1.0477+03 -9.0289+01 -5.0966+01 -3.3645+01    0.88527  8.8786+01
 20.0 TO 25.0 -1.0405+03 -8.9567+01 -6.5004+01 -4.3697+01    0.90146  1.1604+02
 25.0 TO 30.0 -1.0318+03 -8.8719+01 -7.8697+01 -5.3593+01    0.91325  1.4339+02
 30.0 TO 35.0 -1.0214+03 -8.7745+01 -9.1985+01 -6.2703+01    0.91413  1.6923+02
 35.0 TO 40.0 -1.0094+03 -8.6646+01 -1.048 +02 -7.1439+01    0.91407  1.9472+02
 40.0 TO 45.0 -9.9579+02 -1.1928+02 -1.2263+02 -8.3183+01    0.90958  1.7534+02
 45.0 TO 50.0 -9.8054+02 -1.192 +02 -1.3698+02 -9.2912+01    0.90960  1.9595+02
 50.0 TO 55.0 -9.6368+02 -1.1915+02 -1.5133+02 -1.0264+02    0.90961  2.1657+02
 55.0 TO 60.0 -9.452 +02 -1.7868+02 -1.657 +02 -1.1167+02    0.90379  1.691 +02
 60.0 TO 65.0 -9.2509+02 -1.7868+02 -1.8011+02 -1.2138+02    0.90379  1.8381+02
 65.0 TO 70.0 -9.0337+02 -1.7872+02 -1.9456+02 -1.3112+02    0.90379  1.985 +02

   VEHICLE         ALPHA   PPCUM INPUT   nPCUM     PCUT INPUT   BATTERY     BATTERY    BATTERY     BATTERY
    SPEED                    POWER     EFFICIENCY   CURRENT      POWER      VOLTAGE    CURRENT      LOSS
     MPH                      KW                     AMPS         KW           V         AMPS        KW


    0.0 TO  5.0   0.98408 -1.4821+00    0.47961 -6.1062+00 -7.6355+00  2.4273+02 -3.1456+01  8.5098-02
    5.0 TO 10.0   0.87646 -1.1621+01    0.87719 -4.7249+01 -1.7019+01  2.4595+02 -6.9196+01  4.1178-01
   10.0 TO 15.0   0.76995 -2.1831+01    0.92995 -8.7627+01 -2.6472+01  2.4914+02 -1.0625+02  9.7092-01
   15.0 TO 20.0   0.66536 -3.1585+01    0.95065 -1.268 +02 -3.5865+01  2.5222+02 -1.4219+02  1.7388+00
   20.0 TO 25.0   0.56272 -4.2023+01    0.96168 -1.6466+02 -4.5133+01  2.552 +02 -1.7684+02  2.6897+00
   25.0 TO 30.0   0.46166 -5.1907+01    0.96853 -2.0112+02 -5.4267+01  2.5809+02 -2.1026+02  3.8022+00
   30.0 TO 35.0   0.36829 -6.1008+01    0.97296 -2.3405+02 -6.2589+01  2.6065+02 -2.4012+02  4.9588+00
   35.0 TO 40.0   0.27735 -6.9737+01    0.97617 -2.6512+02 -7.0463+01  2.6304+02 -2.6788+02  6.1713+00
   40.0 TO 45.0   0.35704 -8.1204+01    0.97620 -3.0501+02 -8.1204+01  2.6623+02 -3.0501+02  8.0008+00
   45.0 TO 50.0   0.28737 -9.0913+01    0.97848 -3.3789+02 -9.0913+01  2.6906+02 -3.3789+02  9.8186+00
   50.0 TO 55.0   0.21858 -1.0062+02    0.98032 -3.7018+02 -1.0062+02  2.7184+02 -3.7018+02  1.1784+01
   55.0 TO 60.0   0.35655 -1.0922+02    0.97800 -3.9825+02 -1.0922+02  2.7425+02 -3.9825+02  1.364 +01
   60.0 TO 65.0   0.34581 -1.189 +02    0.97956 -4.2938+02 -1.189 +02  2.7693+02 -4.2938+02  1.5855+01
   65.0 TO 70.0   0.30350 -1.2862+02    0.98090 -4.6008+02 -1.2862+02  2.7957+02 -4.6008+02  1.8203+01
```

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PARALLEL EPT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .CE6 CHMS
ETA(GO) =  .900

ACCELERATICN = -5.25 TC -4.25 MPH/SEC

   VEHICLE      TORCUE       MJTOR       MOTOR       POWER      MOTOR      TERMINAL
    SPEED      AT WHEEL      TORQUE      POWER       INPUT    EFFICIENCY    VOLTAGE
     MPH        FT-LB        FT-LB        HP          KW                      V

  0.0 TO  5.0 -8.6363+C2 -7.5957+01 -6.1284+00 -2.5464+00    0.55766   7.6486+00
  5.0 TO 10.0 -8.6133+02 -7.5687+01 -1.831 +01 -1.1022+01    0.80729   3.3179+01
 10.0 TO 15.0 -8.5742+C2 -7.5249+01 -3.034 +01 -1.9472+01    0.86066   5.6657+01
 15.0 TO 20.0 -8.5168+02 -7.4603+01 -4.2157+01 -2.7616+01    0.89485   8.4535+01
 20.0 TO 25.0 -8.4473+C2 -7.3989+01 -5.3698+01 -3.0075+01    0.90091   1.1036+02
 25.0 TO 30.0 -8.3596+02 -7.317 +01 -6.4904+C1 -4.4C97+01    0.91111   1.3598+02
 30.0 TO 35.0 -8.2557+C2 -7.2224+01 -7.5714+01 -5.1567+01    0.91333   1.6049+02
 35.0 TO 40.0 -8.1356+02 -7.1154+01 -8.6068+01 -5.8615+01    0.91327   1.8436+02
 40.0 TO 45.0 -7.9553+02 -9.8663+01 -1.0144+02 -6.9151+01    0.91416   1.7002+02
 45.0 TO 50.0 -7.8469+02 -9.8625+01 -1.1333+02 -7.7256+01    0.91417   1.9001+02
 50.0 TO 55.0 -7.6782+02 -9.861 +01 -1.2524+02 -8.5378+01    0.91417   2.1001+02
 55.0 TO 60.0 -7.4934+02 -1.4793+02 -1.3718+02 -9.2469+01    0.90392   1.657 +02
 60.0 TO 65.0 -7.2924+02 -1.4758+02 -1.4916+02 -1.0C54+02    0.90391   1.8012+02
 65.0 TO 70.0 -7.0751+02 -1.48C8+02 -1.612 +02 -1.0665+02    0.90389   1.9455+02

   VEHICLE        ALPHA    P PCUM INPUT   η PCUM     PCUT INPUT  BATTERY    BATTERY    BATTERY    BATTERY
    SPEED                      POWER    EFFICIENCY   CURRENT     POWER      VOLTAGE    CURRENT     LOSS
     MPH                        KW                    AMPS        KW          V         AMPS        KW

  0.0 TO  5.0     C.58695 -1.0549+00    0.41394 -4.3482+00 -7.2082+00  2.426 +02 -2.9711+01  7.5918-C2
  5.0 TO 10.0     C.8832C -9.5152+00    0.86324 -3.68   +01 -1.4913+01  2.4523+02 -6.0812+01  3.1803-C1
 10.0 TO 15.0     0.78106 -1.7952+01    0.92192 -7.2432+01 -2.2592+01  2.4784+C2 -9.1156+01  7.1461-01
 15.0 TO 20.0     C.68C93 -2.6285+01    0.94494 -1.0498+02 -3.0165+01  2.5036+02 -1.2048+02  1.2484+00
 20.0 TO 25.0     0.582C8 -3.4534+01    0.95727 -1.366 +02 -3.7645+01  2.5281+02 -1.489 +02  1.9C68+00
 25.0 TO 30.0     0.48573 -4.2548+01    0.96487 -1.6676+02 -4.4907+01  2.5513+02 -1.7601+02  2.6643+00
 30.0 TO 35.0     C.39492 -5.0012+01    0.96985 -1.9441+02 -5.1593+01  2.5725+02 -2.0C55+02  3.4592+00
 35.0 TO 40.0     0.30354 -5.7057+01    0.97342 -2.2014+02 -5.7783+01  2.5917+02 -2.2295+02  4.2748+00
 40.0 TO 45.0     0.36810 -6.736 +01    0.97409 -2.57   +02 -6.736 +01  2.621 +02 -2.57   +02  5.6801+C0
 45.0 TO 50.0     0.29848 -7.545 +01    0.97660 -2.8522+02 -7.545 +01  2.6453+02 -2.8522+02  6.9963+00
 50.0 TO 55.0     0.230C0 -8.3554+01    0.97863 -3.1303+02 -8.3554+01  2.6692+02 -3.1303+02  8.4268+00
 55.0 TO 60.0     0.39831 -9.0281+01    0.97633 -3.3577+02 -9.0281+01  2.6888+02 -3.3577+02  9.6957+00
 60.0 TO 65.0     0.35038 -9.8338+01    0.97804 -3.6262+02 -9.8338+01  2.7119+02 -3.6262+C2  1.1308+C1
 65.0 TO 70.0     0.30314 -1.0643+02    0.97950 -3.8919+02 -1.0643+02  2.7347+02 -3.8919+02  1.3026+01
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PARALLEL EHT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GC) =  .900

ACCELERATION = -4.25 TO -3.25 MPH/SEC


   VEHICLE      TORQUE      MOTOR       MOTOR       POWER      MOTOR      TERMINAL
    SPEED      AT WHEEL     TORQUE      POWER       INPUT    EFFICIENCY    VOLTAGE
     MPH        FT-LB       FT-LB        HP          KW                       V


  0.0 TO  5.0 -6.6777+02 -6.0305+01 -4.863 +00 -2.01   +00    0.55429   7.1986+00
  5.0 TO 10.0 -6.6548+02 -6.0024+01 -1.452 +01 -8.7795+00    0.81079   3.1557+01
 10.0 TO 15.0 -6.6156+02 -5.9614+01 -2.4036+01 -1.5451+01    0.86204   5.5836+01
 15.0 TO 20.0 -6.5602+02 -5.9076+01 -3.3347+01 -2.1584+01    0.88407   8.0009+01
 20.0 TO 25.0 -6.4887+02 -5.8412+01 -4.2393+01 -2.8439+01    0.89963   1.0441+02
 25.0 TO 30.0 -6.401 +02 -5.7621+01 -5.1112+01 -3.4616+01    0.90822   1.2844+02
 30.0 TO 35.0 -6.2571+02 -5.6704+01 -5.9444+01 -4.0415+01    0.91174   1.5183+02
 35.0 TO 40.0 -6.177 +02 -5.5662+01 -6.7329+01 -4.578 +01    0.91183   1.7447+02
 40.0 TO 45.0 -6.0407+02 -7.8045+01 -8.0242+01 -5.4669+01    0.91363   1.6095+02
 45.0 TO 50.0 -5.8883+02 -7.8045+01 -8.9683+01 -6.1101+01    0.91363   1.7989+02
 50.0 TO 55.0 -5.7196+02 -7.8068+01 -9.9153+01 -6.7552+01    0.91363   1.9884+02
 55.0 TO 60.0 -5.5348+02 -1.1717+02 -1.0866+02 -7.3741+01    0.91005   1.5773+02
 60.0 TO 65.0 -5.3338+02 -1.1720+02 -1.1822+02 -8.0227+01    0.91002   1.7147+02
 65.0 TO 70.0 -5.1166+02 -1.1744+02 -1.2785+02 -8.6757+01    0.90999   1.8523+02

   VEHICLE       ALPHA    PPCUN INPUT    nPCUN     PCUT INPUT   BATTERY     BATTERY    BATTERY     BATTERY
    SPEED                    POWER     EFFICIENCY   CURRENT      POWER      VOLTAGE    CURRENT      LOSS
     MPH                      KW                     AMPS         KW           V         AMPS         KW


  0.0 TO  5.0    0.99049 -6.4336-01    0.32007 -2.6535+00 -6.7966+00   2.4245+02 -2.8033+01   6.7584-02
  5.0 TO 10.0    0.89116 -7.4037+00    0.84329 -3.0279+01 -1.2801+01   2.4451+02 -5.2357+01   2.3574-01
 10.0 TO 15.0    0.79379 -1.4067+01    0.91045 -5.7061+01 -1.8708+01   2.4653+02 -7.5886+01   4.9522-01
 15.0 TO 20.0    0.65835 -2.0594+01    0.93678 -8.2883+01 -2.4474+01   2.4847+02 -9.8499+01   8.3438-01
 20.0 TO 25.0    0.60338 -2.7045+01    0.95096 -1.0802+02 -3.0155+01   2.5036+02 -1.2044+02   1.2476+00
 25.0 TO 30.0    0.51112 -3.3219+01    0.95963 -1.3175+02 -3.5578+01   2.5213+02 -1.411 +02   1.7124+00
 30.0 TO 35.0    0.42234 -3.9017+01    0.96541 -1.5375+02 -4.0599+01   2.5378+02 -1.5998+02   2.2012+00
 35.0 TO 40.0    0.33715 -4.4384+01    0.96950 -1.7391+02 -4.511 +01   2.552 +02 -1.7676+02   2.6871+00
 40.0 TO 45.0    0.39374 -5.3066+01    0.97069 -2.0591+02 -5.3066+01   2.5771+02 -2.0591+02   3.6445+00
 45.0 TO 50.0    0.32561 -5.9486+01    0.97357 -2.2905+02 -5.9486+01   2.597 +02 -2.2905+02   4.5121+00
 50.0 TO 55.0    0.25840 -6.5925+01    0.97591 -2.5194+02 -6.5925+01   2.6167+02 -2.5194+02   5.4588+00
 55.0 TO 60.0    0.41702 -7.1798+01    0.97365 -2.7254+02 -7.1798+01   2.6344+02 -2.7254+02   6.388 +00
 60.0 TO 65.0    0.36958 -7.827 +01    0.97559 -2.9485+02 -7.827 +01   2.6537+02 -2.9485+02   7.4815+00
 65.0 TO 70.0    0.32274 -8.4783+01    0.97725 -3.1721+02 -8.4783+01   2.6728+02 -3.1721+02   8.6533+00
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PARALLEL EPT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .C86 OHMS
ETA(GG) =  .900

ACCELERATICN = -3.25 TO -2.25 MPH/SEC

   VEHICLE       TCRGUE      MOTOR       MOTOR       POWER       MOTOR     TERMINAL
    SPEED       AT WHEEL     TURQUE      POWER       INPUT     EFFICIENCY   VOLTAGE
     MPH         FT-LB       FT-LB        HP          KW                       V


   0.0 TO  5.0 -4.7192+02 -4.4613+01 -3.5976+00 -1.413 +00    0.52670  6.3764+00
   5.0 TO 10.0 -4.6962+02 -4.436 +01 -1.0731+01 -6.4692+00    0.81089  2.9408+01
  10.0 TU 15.0 -4.657 +C2 -4.3579+01 -1.7732+01 -1.1357+01    0.85887  5.18  +01
  15.0 TO 20.0 -4.6C17+02 -4.347 +01 -2.4538+01 -1.6102+01    0.88003  7.4084+01
  20.0 TO 25.0 -4.5301+02 -4.2834+01 -3.1087+01 -2.0722+01    0.89309  9.6381+01
  25.0 TO 30.0 -4.4424+02 -4.2071+01 -3.7319+01 -2.5128+01    0.90295  1.1843+02
  30.0 TO 35.0 -4.3385+02 -4.1183+01 -4.3173+01 -2.9231+01    0.90797  1.3994+02
  35.0 TO 40.0 -4.2184+02 -4.C17 +01 -4.859 +01 -3.2941+C1    0.90915  1.6059+02
  40.0 TO 45.0 -4.0821+02 -5.7427+01 -5.9044+01 -4.0147+01    0.91182  1.4936+02
  45.0 TO 50.0 -3.9297+02 -5.7465+01 -6.6035+01 -4.4915+01    0.91214  1.6701+02
  50.0 TO 55.0 -3.761 +02 -5.7527+01 -7.3063+01 -4.9657+01    0.91215  1.8464+02
  55.0 TO 60.0 -3.5762+02 -8.6419+01 -8.0141+01 -5.4603+01    0.91368  1.4913+02
  60.0 TO 65.0 -3.3752+02 -8.6588+01 -8.728 +01 -5.9492+01    0.91407  1.6224+02
  65.0 TO 70.0 -3.158 +C2 -8.6759+01 -9.4493+01 -6.441 +01    0.91408  1.7532+02

   VEHICLE        ALPHA   P PCUM INPUT  n PCUM     PCUT INPUT   BATTERY     BATTERY     BATTERY     BATTERY
    SPEED                    POWER    EFFICIENCY    CURRENT      POWER      VOLTAGE     CURRENT      LOSS
     MPH                      KW                     AMPS         KW           V          AMPS        KW


   0.0 TO  5.0     0.55652 -1.8645-01   0.13195 -7.6945-01 -6.3397+00  2.4231+02 -2.6163+01  5.8868-C2
   5.0 TO 10.0     0.90225 -5.2576+00   0.81020 -2.1568+01 -1.0655+01  2.4377+02 -4.3712+01  1.6432-01
  10.0 TO 15.0     0.8117C -1.0121+01   0.89123 -4.1262+01 -1.4762+01  2.4518+02 -6.0208+01  3.1175-C1
  15.0 TO 20.0     0.72259 -1.4665+01   0.92316 -6.0296+01 -1.8745+01  2.4654+02 -7.6035+01  4.9719-01
  20.0 TO 25.0     0.63435 -1.9484+01   0.94026 -7.8614+01 -2.2595+01  2.4784+02 -9.1165+01  7.1476-C1
  25.0 TO 30.0     0.54789 -2.3891+01   0.95078 -9.5924+01 -2.6251+01  2.4906+02 -1.0539+02  9.5536-C1
  30.0 TO 35.0     0.46421 -2.7998+01   0.95779 -1.1191+02 -2.9579+01  2.5017+02 -1.1823+02  1.2C22+00
  35.0 TO 40.0     0.38432 -3.1713+01   0.96269 -1.2629+02 -3.2439+01  2.5111+02 -1.2918+02  1.4351+C0
  40.0 TO 45.0     0.43061 -3.8746+01   0.96510 -1.5304+02 -3.9746+01  2.5316+02 -1.5304+02  2.0144+00
  45.0 TO 50.0     0.36483 -4.3505+01   0.96861 -1.7081+02 -4.3505+01  2.5469+02 -1.7C81+02  2.5093+00
  50.0 TO 55.0     0.29990 -4.8278+01   0.97145 -1.8843+02 -4.8278+01  2.5621+02 -1.8843+02  3.0536+C0
  55.0 TO 60.0     0.43885 -5.2937+01   0.96949 -2.0544+02 -5.2937+01  2.5767+02 -2.0544+02  3.6299+00
  60.0 TO 65.0     0.39166 -5.7815+01   0.97181 -2.2306+02 -5.7815+01  2.5919+02 -2.2306+02  4.2791+00
  65.0 TO 70.0     0.34511 -6.2721+01   0.97378 -2.4059+02 -6.2721+01  2.6069+02 -2.4C59+02  4.5781+00
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PARALLEL EMT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GO) =  .900

ACCELERATION = -2.25 TO -1.25 MPH/SEC

    VEHICLE      TORQUE       MOTOR        MOTOR        POWER        MOTOR       TERMINAL
     SPEED      AT WHEEL      TORQUE       POWER        INPUT      EFFICIENCY    VOLTAGE
      MPH        FT-LB        FT-LB         HP           KW                         V

   0.0 TO  5.0 -2.7606+02 -2.6921+01 -2.3322+00 -6.0775-01     0.46446   4.9931+00
   5.0 TO 10.0 -2.7376+02 -2.8657+01 -6.9424+00 -4.1477+00     0.80120   2.5298+01
  10.0 TO 15.0 -2.6984+02 -2.8344+01 -1.1428+01 -7.2256+00     0.84832   4.4433+01
  15.0 TO 20.0 -2.6431+02 -2.7864+01 -1.5728+01 -1.0176+01     0.86767   6.3206+01
  20.0 TO 25.0 -2.5715+02 -2.7256+01 -1.9781+01 -1.2566+01     0.87901   8.1619+01
  25.0 TO 30.0 -2.4838+02 -2.6522+01 -2.3526+01 -1.5555+01     0.88691   9.9567+01
  30.0 TO 35.0 -2.3799+02 -2.5663+01 -2.6903+01 -1.7882+01     0.89139   1.1669+02
  35.0 TO 40.0 -2.2598+02 -2.4678+01 -2.9851+01 -1.9884+01     0.89327   1.3277+02
  40.0 TO 45.0 -2.1235+02 -3.6809+01 -3.7845+01 -2.5519+01     0.90424   1.3245+02
  45.0 TO 50.0 -1.971  +02 -3.6886+01 -4.2386+01 -2.8656+01     0.90662   1.4852+02
  50.0 TO 55.0 -1.8024+02 -3.6985+01 -4.6974+01 -3.1766+01     0.90686   1.6432+02
  55.0 TO 60.0 -1.6176+02 -5.5664+01 -5.162 +01 -3.5012+01     0.90956   1.3343+02
  60.0 TO 65.0 -1.4165+02 -5.5889+01 -5.6336+01 -3.8283+01     0.91127   1.4544+02
  65.0 TO 70.0 -1.1593+02 -5.6158+01 -6.1136+01 -4.1572+01     0.91188   1.5735+02

    VEHICLE       ALPHA  P_PCUM INPUT   η_PCUM      PCUT INPUT   BATTERY      BATTERY     BATTERY      BATTERY
     SPEED                  POWER     EFFICIENCY     CURRENT      POWER       VOLTAGE     CURRENT       LOSS
      MPH                    KW                       AMPS          KW           V          AMPS          KW

   0.0 TO  5.0     1.00000  0.     +00    0.00000  0.     +00 -6.1533+00  2.4218+02 -2.5407+01  5.5516-02
   5.0 TO 10.0     0.92312 -3.0629+00    0.73844 -1.2603+01 -8.461  +00  2.4301+02 -3.4816+01  1.0424-01
  10.0 TO 15.0     0.84511 -6.1444+00    0.84989 -2.52   +01 -1.0784+01  2.4381+02 -4.4233+01  1.6826-01
  15.0 TO 20.0     0.76909 -9.0927+00    0.89346 -3.7179+01 -1.2973+01  2.4456+02 -5.3044+01  2.4198-01
  20.0 TO 25.0     0.65458 -1.1884+01    0.91657 -4.8457+01 -1.4995+01  2.4526+02 -6.114  +01  3.2148-01
  25.0 TO 30.0     0.62313 -1.4482+01    0.93073 -5.8894+01 -1.6841+01  2.4589+02 -6.8491+01  4.0342-01
  30.0 TO 35.0     0.55482 -1.681  +01    0.94005 -6.8218+01 -1.8392+01  2.4642+02 -7.4635+01  4.7906-01
  35.0 TO 40.0     0.45087 -1.8819+01    0.94645 -7.6248+01 -1.9545+01  2.4682+02 -7.919  +01  5.3531-01
  40.0 TO 45.0     0.49155 -2.4335+01    0.95361 -9.7957+01 -2.4335+01  2.4842+02 -9.7957+01  8.2522-01
  45.0 TO 50.0     0.42537 -2.7466+01    0.95849 -1.101  +02 -2.7466+01  2.4947+02 -1.101  +02  1.0424+00
  50.0 TO 55.0     0.36868 -3.057  +01    0.96237 -1.2204+02 -3.057  +01  2.5049+02 -1.2204+02  1.2808+00
  55.0 TO 60.0     0.49031 -3.3636+01    0.96069 -1.3374+02 -3.3636+01  2.515  +02 -1.3374+02  1.5382+00
  60.0 TO 65.0     0.44496 -3.6899+01    0.96385 -1.4609+02 -3.6899+01  2.5256+02 -1.4609+02  1.8356+00
  65.0 TO 70.0     0.40035 -4.018  +01    0.96651 -1.5842+02 -4.018  +01  2.5362+02 -1.5842+02  2.1583+00
```

```
PARALLEL EHT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GU) =  .900

ACCELERATION = -1.25 TO -0.75 MPH/SEC

   VEHICLE      TORQUE      MOTOR       MOTOR        POWER       MOTOR      TERMINAL
    SPEED      AT WHEEL     TORQUE      POWER        INPUT     EFFICIENCY   VOLTAGE
     MPH         FT-LB      FT-LB        HP           KW                       V

  0.0 TO  5.0 -1.2516+02 -1.7152+01 -1.3831+00 -4.1516-01     0.40251   3.4538+00
  5.0 TO 10.0 -1.2666+02 -1.6949+01 -4.1004+00 -2.3968+00     0.78387   2.0084+01
 10.0 TO 15.0 -1.2294+02 -1.6618+01 -6.7005+00 -4.1379+00     0.82814   3.5088+01
 15.0 TO 20.0 -1.1741+02 -1.6159+01 -9.1216+00 -5.7738+00     0.84883   4.9787+01
 20.0 TO 25.0 -1.1026+02 -1.5573+01 -1.1302+01 -7.2354+00     0.85847   6.3765+01
 25.0 TO 30.0 -1.0146+02 -1.486  +01 -1.3182+01 -8.4906+00     0.86375   7.6887+01
 30.0 TO 35.0 -9.1098+01 -1.4022+01 -1.47   +01 -9.501  +00     0.86673   8.8915+01
 35.0 TO 40.0 -7.9089+01 -1.3059+01 -1.5796+01 -1.0213+01     0.86700   9.94   +01
 40.0 TO 45.0 -6.5461+01 -2.1345+01 -2.1947+01 -1.4467+01     0.88520   1.0498+02
 45.0 TO 50.0 -5.0215+01 -2.1451+01 -2.4649+01 -1.6331+01     0.88848   1.1802+02
 50.0 TO 55.0 -3.335 +01 -2.1579+01 -2.7407+01 -1.8185+01     0.88979   1.3099+02
 55.0 TO 60.0 -1.4667+01 -3.2557+01 -3.0229+01 -2.0195+01     0.89591   1.1363+02
 60.0 TO 65.0  5.2343+00 -3.2809+01 -3.3072+01 -2.2167+01     0.89886   1.242 +02
 65.0 TO 70.0  2.6554+01 -3.287 +01 -3.5784+01 -2.405 +01     0.90130   1.3459+02

   VEHICLE          ALPHA  P PCUM INPUT   n PCUM     PCUM INPUT  BATTERY    BATTERY    BATTERY    BATTERY
    SPEED                      POWER    EFFICIENCY    CURRENT     POWER     VOLTAGE    CURRENT     LOSS
     MPH                        KW                     AMPS        KW          V         AMPS       KW

  0.0 TO  5.0     1.00000  0.    +00    0.00000  0.    +00 -6.1533+00  2.4218+02 -2.5407+01  5.5516-02
  5.0 TO 10.0     0.95055 -1.4306+00    0.59688 -5.9008+00 -6.8287+00  2.4244+02 -2.8166+01  6.8226-02
 10.0 TO 15.0     0.88914 -3.174 +00    0.76706 -1.3072+01 -7.8145+00  2.4279+02 -3.2185+01  8.9088-02
 15.0 TO 20.0     0.82924 -4.8139+00    0.83375 -1.9802+01 -8.6942+00  2.4309+02 -3.5764+01  1.1    -01
 20.0 TO 25.0     0.77252 -6.2812+00    0.86812 -2.5811+01 -9.392 +00  2.4334+02 -3.8595+01  1.281 -01
 25.0 TO 30.0     0.71945 -7.5439+00    0.88849 -3.0981+01 -9.9036+00  2.435 +02 -4.0671+01  1.4226-01
 30.0 TO 35.0     0.67099 -8.5636+00    0.90132 -3.5156+01 -1.0144+01  2.4358+02 -4.1648+01  1.4917-01
 35.0 TO 40.0     0.62887 -9.2867+00    0.90930 -3.8131+01 -1.0012+01  2.4354+02 -4.1113+01  1.4536-01
 40.0 TO 45.0     0.60139 -1.3462+01    0.92926 -5.5007+01 -1.3462+01  2.4473+02 -5.5007+01  2.6021-01
 45.0 TO 50.0     0.54527 -1.5303+01    0.93702 -6.2367+01 -1.5303+01  2.4537+02 -6.2367+01  3.3451-01
 50.0 TO 55.0     0.45772 -1.7152+01    0.94323 -6.9726+01 -1.7152+01  2.46   +02 -6.9726+01  4.1811-01
 55.0 TO 60.0     0.56521 -1.9059+01    0.94371 -7.727 +01 -1.9059+01  2.4665+02 -7.727 +01  5.1347-01
 60.0 TO 65.0     0.52365 -2.1025+01    0.94849 -8.5013+01 -2.1025+01  2.4732+02 -8.5013+01  6.2155-01
 65.0 TO 70.0     0.48300 -2.2905+01    0.95238 -9.238 +01 -2.2905+01  2.4794+02 -9.238 +01  7.3393-01
```

```
PARALLEL EPT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GO) =  .900                                                                10

ACCELERATICN = -C.75 TC -0.25 MPH/SEC

  VEHICLE      TCRQUE       MOTOR        MOTOR       POWER        MOTOR     TERMINAL
   SPEED      AT WHEEL      TORQUE       POWER       INPUT      EFFICIENCY   VOLTAGE
    MPH        FT-LB        FT-LB         HP          KW                        V

  0.0 TO  5.0 -3.1233+01 -9.3061+00 -7.5045-01 -2.0292-01     0.36262  2.3396+00
  5.0 TU 10.0 -2.8536+01 -9.1178+00 -2.2057+00 -1.2475+00     0.75845  1.4517+01
 10.0 TO 15.0 -2.5019+01 -8.801 +00 -3.5485+00 -2.1078+00     0.79654  2.492 +01
 15.0 TO 20.0 -1.5464+01 -8.3563+00 -4.7169+00 -2.8649+00     0.81448  3.4649+01
 20.0 TO 25.0 -1.2331+01 -7.7845+00 -5.6497+00 -3.4562+00     0.82084  4.3213+01
 25.0 TO 30.0 -3.5594+C0 -7.0863+00 -6.2858+00 -3.8613+00     0.82378  5.048 +01
 30.0 TO 35.0  6.831 +00 -6.2379+00 -6.5393+00 -4.001 +00     0.82049  5.5418+01
 35.0 TO 40.0  1.884 +01 -5.2403+00 -6.3386+00 -3.8545+00     0.81548  5.7405+01
 40.0 TO 45.0  3.2467+01 -1.0855+01 -1.1161+01 -7.0918+00     0.85206  7.5973+01
 45.0 TO 50.0  4.7713+01 -1.0875+01 -1.2497+01 -7.9659+00     0.85476  8.5259+01
 50.0 TO 55.0  6.4578+C1 -1.0896+01 -1.3838+C1 -8.6394+C0     0.85656  9.4521+01
 55.0 TO 60.0  8.3061+C1 -1.6374+01 -1.5184+01 -9.8448+00     0.86942  8.4225+01
 60.0 TO 65.0  1.0316+C2 -1.64C4+01 -1.6536+01 -1.0752+01     0.87198  9.1887+01
 65.0 TO 70.0  1.2488+02 -1.6435+01 -1.7892+01 -1.1659+01     0.87384  9.9525+01

  VEHICLE        ALPHA  PPCUM INPUT    ηPCUM    PCUT INPUT   BATTERY     BATTERY    BATTERY     BATTERY
   SPEED                   POWER     EFFICIENCY   CURRENT      POWER     VOLTAGE    CURRENT      LOSS
    MPH                     KW                     AMPS         KW          V        AMPS         KW

  0.0 TO  5.0     1.CCCCC  0.     +00    0.00000  0.     +00 -6.1533+00  2.4218+02 -2.5407+01  5.5516-C2
  5.0 TO 10.0     0.98211 -3.7199-01    0.29818 -1.5367+C0 -5.77   +00  2.4206+02 -2.3836+01  4.8864-C2
 10.0 TO 15.0     C.93966 -1.2356+00    0.58621 -5.1C29+00 -5.8761+00  2.4213+02 -2.4267+01  5.0646-C2
 15.0 TO 20.0     0.90020 -1.9979+00    0.69736 -8.2512+C0 -5.8781+00  2.4213+02 -2.4276+01  5.0683-02
 20.0 TO 25.0     0.86586 -2.5986+00    0.75143 -1.0734+01 -5.7093+00  2.4207+02 -2.3585+01  4.7839-02
 25.0 TO 30.0     0.83726 -3.0118+00    0.77998 -1.2447+01 -5.3715+00  2.4195+02 -2.22   +01  4.2387-02
 30.0 TO 35.0     C.81865 -3.1639+00    0.79078 -1.3C89+01 -4.7453+00  2.4171+02 -1.9632+01  3.3146-C2
 35.0 TO 40.0     0.81289 -3.0324+00    0.78671 -1.2563+01 -3.7586+00  2.4137+02 -1.5572+01  2.C854-C2
 40.0 TO 45.0     0.72596 -6.1957+00    0.87364 -2.5579+01 -6.1957+00  2.4221+02 -2.5579+01  5.6271-C2
 45.0 TO 50.0     0.68804 -7.0684+00    0.88734 -2.9145+01 -7.0684+00  2.4252+02 -2.9145+01  7.3055-02
 50.0 TO 55.0     0.65031 -7.9406+00    0.89832 -3.2701+01 -7.9406+00  2.4282+02 -3.2701+01  9.1968-C2
 55.0 TO 60.0     0.68748 -8.8822+00    0.90222 -3.6528+C1 -8.8822+00  2.4315+02 -3.6528+01  1.1475-01
 60.0 TO 65.0     0.65643 -9.7881+00    0.91033 -4.0202+01 -9.7881+00  2.4346+02 -4.0202+01  1.3899-01
 65.0 TO 70.0     0.62556 -1.C693+01    0.91717 -4.3863+01 -1.0693+01  2.4378+02 -4.3863+01  1.6946-C1
```

```
PARALLEL EPT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GO) =  .9CC

ACCELERATICN = -0.25 TC  0.25 MPH/SEC                                                                    11

  VEHICLE      TORQUE       MOTOR        MOTOR        POWER
   SPEED      AT WHEEL      TORQUE       POWER        INPUT       MOTOR       TERMINAL
    MPH        FT-LB        FT-LB         HP           KW       EFFICIENCY     VOLTAGE
                                                                                 V

  0.0 TO  5.0  6.6695+01 -1.3395+00 -1.0801-01 -4.2886-02
  5.0 TO 10.C  6.8593+01 -1.14C9+00 -2.7601-01 -1.4696-01     0.53242   9.0476-01
 10.0 TO 15.0  7.29C9+01 -8.0856-01 -3.2601-01 -1.7823-01     0.71402   3.1676+00
 15.0 TO 20.0  7.8444+C1 -3.4164-01 -1.9285-01 -1.0657-01     0.73316   3.9862+00
 20.0 TO 25.0  8.5557+C1  2.7132-01  1.9691-01  1.9619-01     0.74111   2.5166+00
 25.0 TO 30.0  9.4369+01  1.04  +00  9.2254-01  9.0123-01     0.74842   4.6721+00
 30.0 TO 35.0  1.0476+02  1.9511+00  2.0454+00  1.9651+00     0.76333   1.9641+01
 35.0 TO 40.0  1.1676+02  3.0055+00  3.6354+00  3.425  +00     0.77617   3.8915+01
 40.0 TO 45.0  1.3C39+02 -7.272  -06 -7.4768-06 -4.2095-06     0.79149   6.1343+01
 45.0 TO 50.0  1.4564+C2  0.     +00  0.     +00  0.     +00     0.75500   1.0363-04
 50.0 TO 55.0  1.625  +02  0.     +00  0.     +00  0.     +00     0.75777   0.     +00
 55.0 TO 60.0  1.8C99+02 -3.2249-05 -2.9907-05 -1.6792-05     0.76044   0.     +00
 60.0 TO 65.0  2.0109+02  0.     +00  0.     +00  0.     +00     0.75297   4.1341-04
 65.0 TO 70.0  2.2281+02  1.3736-05  1.4953-05  8.4341-06     0.75460   0.     +00
                                                              0.75636  -2.0763-04

  VEHICLE      ALPHA    PPCUM INPUT    nPCUM     PCUT INPUT   BATTERY     BATTERY     BATTERY     BATTERY
   SPEED                   POWER     EFFICIENCY    CURRENT      POWER     VOLTAGE     CURRENT      LOSS
    MPH                     KW                      AMPS         KW          V          AMPS         KW

  0.0 TO  5.0  1.CCOCC  0.     +00   0.00000   0.     +00
  5.0 TO 10.0  1.00000  0.     +00   0.00000   0.     +00 -6.1533+00  2.4218+02 -2.5407+0.
 10.0 TO 15.0  1.00000  0.     +00   0.00000   0.     +00 -5.398  +00  2.4191+02 -2.2313+0.  5.5516-C2
 15.0 TO 20.0  1.C0000  0.     +00   0.00000   0.     +00 -4.6405+00  2.4165+02 -1.9203+01  4.2819-02
 20.0 TO 25.0  0.09600  9.6842-01   0.20259   4.0314+00 -3.8802+00  2.4138+02 -1.6075+01  3.1714-02
 25.0 TO 30.0  0.15304  1.6865+00   0.53436   7.0224+00 -2.1423+00  2.4021+02 -8.9183+00  2.2223-02
 30.0 TO 35.0  0.22851  2.764  +00   0.71094   1.1539+01 -6.7318-01  2.4016+02 -2.803  +00  6.8402-03
 35.0 TO 40.0  0.31810  4.2394+00   0.80791   1.776  +01  1.1826+00  2.3953+02  4.9374+00  6.7569-04
 40.0 TO 45.0  1.CC000  0.     +00   0.00000   0.     +00  3.5132+00  2.3869+02  1.4718+01  2.0965-03
 45.0 TO 50.0  1.00000  0.     +00   0.00000   0.     +00  0.     +00  2.4    +02  0.     +00  1.863  -02
 50.0 TO 55.0  1.00000  0.     +00   0.00000   0.     +00  0.     +00  2.4    +02  0.     +00  0.     +00
 55.0 TO 60.0  1.00000  0.     +00   0.00000   0.     +00  0.     +00  2.4    +02  0.     +00  0.     +00
 60.0 TO 65.0  1.00C00  0.     +00   0.00000   0.     +00  0.     +00  2.4    +02  0.     +00  0.     +00
 65.0 TO 70.0  1.00000  0.     +00   0.00000   0.     +00  0.     +00  2.4    +02  0.     +00  0.     +00
                                                                     2.4    +02  0.     +00  0.     +00
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```
PARALLEL EMT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GO) =  .9CC

ACCELERATION =  0.25 TC  C.75 MPH/SEC

  VEHICLE      TORQUE      MOTOR       MOTOR       POWER       MOTOR      TERMINAL
   SPEED      AT WHEEL     TORQUE      POWER       INPUT     EFFICIENCY   VOLTAGE
    MPH        FT-LB       FT-LB        HP          KW                       V

  0.0 TO  5.0  1.6462+02  6.9552+00  5.6119-01  1.1913+00    0.35125  1.5707+01
  5.0 TO 1C.C  1.6692+C2  7.1512+00  1.7372+00  1.7302+C0    0.74473  2.2478+01
 10.0 TO 15.0  1.7C83+02  7.5426+00  3.0411+00  2.6739+C0    0.74939  3.647 +01
 15.0 TU 20.0  1.7637+C2  8.0441+00  4.5407+00  4.1675+C0    0.81248  5.1234+01
 20.0 TO 25.0  1.8352+02  8.6866+00  6.3044+00  5.6845+00    0.82701  6.7598+01
 25.0 TO 30.0  1.9229+02  9.47C8+00  8.40C9+00  7.4622+00    0.83959  8.5343+01
 30.0 TO 35.0  2.0268+02  1.0397+01  1.0899+01  9.5675+00    0.84953  1.0468+02
 35.0 TU 40.0  2.1469+02  1.1467+01  1.387 +01  1.2035+C1    0.85939  1.2543+02
 40.0 TO 45.0  2.2832+02  1.1303+01  1.1621+01  1.0136+01    0.85494  1.0641+02
 45.0 TU 50.0  2.4357+02  1.1324+01  1.3012+01  1.1315+01    0.85759  1.1967+02
 50.0 TO 55.0  2.6044+02  1.1345+01  1.4409+01  1.2503+C1    0.85938  1.3101+02
 55.0 TO 60.0  2.7852+02  1.7049+01  1.581 +01  1.3534+01    0.87113  1.13  +02
 60.0 TO 65.0  2.9502+02  1.7C81+01  1.7217+01  1.4694+01    0.87373  1.2255+02
 65.0 TU 70.0  3.2074+C2  1.7113+01  1.863 +01  1.5865+01    0.87561  1.3217+02

   VEHICLE      ALPHA    PPCUM INPUT    ηPCUM      PLUT INPUT    BATTERY     BATTERY     BATTERY     BATTERY
    SPEED                  POWER      EFFICIENCY    CURRENT       POWER      VOLTAGE     CURRENT      LOSS
     MPH                    KW                        AMPS         KW           V          AMPS        KW

  0.0 TO  5.0   0.11383   2.0846+00    0.57148    8.6344+00  -4.0686+00  2.4143+02  -1.6851+01  2.4421-02
  5.0 TO 10.0   0.14155   2.6258+00    0.65893    1.0895+01  -2.7722+00  2.4099+02  -1.1503+01  1.138 -C2
 10.0 TU 15.0   0.19924   3.7734+00    0.76162    1.5701+01  -8.6706-01  2.4032+02  -3.6C78+00  1.1194-C3
 15.0 TO 20.0   C.26049   5.0723+00    0.82161    2.1169+01   1.192 +00  2.3938+02   4.9797+00  2.1325-C3
 20.0 TU 25.0   0.32858   6.5564+00    0.86175    2.7631+01   3.4856+00  2.3873+02   1.46  +01  1.8333-02
 25.0 TG 30.0   0.40312   8.3823+00    0.89023    3.5248+01   6.0225+00  2.378 +02   2.5325+01  5.5157-02
 30.0 TU 35.0   0.48516   1.0457+01    0.91143    4.4339+01   8.9157+00  2.3674+02   3.766 +01  1.2197-C1
 35.0 TO 40.0   0.57420   1.2976+01    0.92751    5.5C97+01   1.225 +01  2.3551+02   5.2C14+01  2.3266-C1
 40.0 TO 45.0   0.49282   1.1C76+01    0.91514    4.6944+01   1.1076+01  2.3594+02   4.6944+01  1.8552-C1
 45.0 TO 50.0   0.54568   1.2253+01    0.92340    5.2C27+01   1.2253+01  2.3551+02   5.2C27+01  2.3279-01
 50.0 TO 55.0   0.59910   1.344 +01    0.93028    5.7174+01   1.344 +01  2.3507+02   5.7174+01  2.8113-C1
 55.0 TO 60.0   0.51786   1.4554+01    0.92990    6.2023+01   1.4554+01  2.3466+02   6.2C23+01  3.3082-C1
 60.0 TO 65.0   0.55952   1.5713+01    0.93516    6.7C87+01   1.5713+01  2.3422+02   6.7C87+01  3.8706-C1
 65.0 TO 70.0   0.60162   1.6883+01    0.93974    7.2217+01   1.6883+01  2.3378+02   7.2217+01  4.4852-C1
```

```
PARALLEL EHT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .066 OHMS
ETA(GJ) =  .900

ACCELERATION =  0.75 TO  1.25 MPH/SEC


   VEHICLE       TORQUE       MOTOR       MOTOR        POWER       MOTOR      TERMINAL
    SPEED       AT WHEEL      TORQUE      POWER        INPUT     EFFICIENCY    VOLTAGE
     MPH         FT-LB        FT-LB        HP           KW                       V


  0.0 TO  5.0  2.6255+02  1.5313+01  1.2346+00  2.3466+00    0.39240  2.0885+01
  5.0 TO 10.0  2.6485+02  1.555 +01  3.7019+00  3.5931+00    0.78073  3.1693+01
 10.0 TO 15.0  2.6877+02  1.5927+01  6.4216+00  5.7959+00    0.82621  5.0409+01
 15.0 TO 20.0  2.743 +02  1.6444+01  9.2823+00  8.1482+00    0.84948  6.9534+01
 20.0 TO 25.0  2.8146+02  1.7101+01  1.2411+01  1.0737+01    0.86201  8.9483+01
 25.0 TO 30.0  2.9023+02  1.7901+01  1.5879+01  1.3587+01    0.87147  1.101 +02
 30.0 TO 35.0  3.0062+02  1.6843+01  1.9754+01  1.6754+01    0.87922  1.3148+02
 35.0 TO 40.0  3.1263+02  1.5929+01  2.4106+01  2.0305+01    0.88528  1.5377+02
 40.0 TO 45.0  3.2626+02  2.2006+01  2.3243+01  1.9535+01    0.88725  1.3713+02
 45.0 TO 50.0  3.415 +02  2.2648+01  2.6025+01  2.1797+01    0.89034  1.5286+02
 50.0 TO 55.0  3.5837+02  2.269 +01  2.8818+01  2.4109+01    0.89135  1.6889+02
 55.0 TO 60.0  3.7665+02  3.4059+01  3.1622+01  2.6267+01    0.89770  1.4352+02
 60.0 TO 65.0  3.5695+02  3.4162+01  3.4435+01  2.8517+01    0.90046  1.5562+02
 65.0 TO 70.0  4.1667+02  3.4226+01  3.726 +01  3.077 +01    0.90297  1.6771+02

   VEHICLE       ALPHA   PPCUM INPUT   PPCUM      PCUT INPUT   BATTERY     BATTERY     BATTERY     BATTERY
    SPEED                   POWER    EFFICIENCY    CURRENT      POWER      VOLTAGE     CURRENT      LOSS
     MPH                     KW                     AMPS         KW           V          AMPS        KW


  0.0 TO  5.0   0.12438  3.3675+00    0.69683  1.3975+01 -2.7857+00  2.4095+02 -1.1561+01  1.1494-02
  5.0 TO 10.0   0.16940  4.6148+00    0.77859  1.9205+01 -7.8321-01  2.4028+02 -3.2594+00  9.1367-04
 10.0 TO 15.0   0.24792  6.8188+00    0.84999  2.8506+01  2.1783+00  2.392 +02  9.1064+00  7.1318-03
 15.0 TO 20.0   0.32884  9.1741+00    0.88817  3.8534+01  5.2938+00  2.3807+02  2.2236+01  4.2522-02
 20.0 TO 25.0   0.41407  1.1767+01    0.91242  4.9685+01  8.6568+00  2.3684+02  3.655 +01  1.1489-01
 25.0 TO 30.0   0.50320  1.4624+01    0.92910  6.2095+01  1.2264+01  2.3551+02  5.2076+01  2.3322-01
 30.0 TO 35.0   0.55686  1.7798+01    0.94131  7.6052+01  1.6217+01  2.3403+02  6.9295+01  4.1295-01
 35.0 TO 40.0   0.65610  2.1358+01    0.95068  9.192 +01  2.0632+01  2.3235+02  8.8795+01  6.7808-01
 40.0 TO 45.0   0.62210  2.0624+01    0.94715  8.8761+01  2.0624+01  2.3236+02  8.8761+01  6.7755-01
 45.0 TO 50.0   0.69323  2.2084+01    0.95252  9.8853+01  2.2084+01  2.3149+02  9.8853+01  8.4039-01
 50.0 TO 55.0   0.76532  2.5192+01    0.95702  1.0924+02  2.5192+01  2.306 +02  1.0924+02  1.0263+00
 55.0 TO 60.0   0.65386  2.7489+01    0.95555  1.1967+02  2.7489+01  2.297 +02  1.1967+02  1.2316+00
 60.0 TO 65.0   0.70915  2.9735+01    0.95904  1.2994+02  2.9735+01  2.2882+02  1.2994+02  1.4522+00
 65.0 TO 70.0   0.76484  3.1984+01    0.96204  1.4032+02  3.1984+01  2.2792+02  1.4032+02  1.6934+00
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PARALLEL EMT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GO) =  .900

ACCELERATION =  2.25 TO  3.25 MPH/SEC

   VEHICLE       TORQUE      MOTOR       MOTOR       POWER      MOTOR      TERMINAL
    SPEED       AT WHEEL     TORQUE      POWER       INPUT    EFFICIENCY   VOLTAGE
     MPH         FT-LB       FT-LB        HP          KW                      V

  0.0 TO  5.0  6.0531+02  4.4552+01  3.5926+00  5.0875+00    0.52659  2.2981+01
  5.0 TO 10.0  6.076 +02  4.4842+01  1.0848+01  9.9762+00    0.81089  4.4847+01
 10.0 TO 15.0  6.1152+02  4.5273+01  1.8254+01  1.5843+01    0.85914  7.0717+01
 15.0 TO 20.0  6.1705+02  4.5843+01  2.5877+01  2.1912+01    0.88065  9.6888+01
 20.0 TO 25.0  6.2421+02  4.6555+01  3.3788+01  2.8143+01    0.89527  1.23  +02
 25.0 TO 30.0  6.3258+02  4.7409+01  4.2053+01  3.466 +01    0.90477  1.4942+02
 30.0 TO 35.0  6.4337+02  4.8405+01  5.0744+01  4.1594+01    0.90974  1.765 +02
 35.0 TO 40.0  6.5538+02  4.9545+01  5.993 +01  4.9068+01    0.91078  2.0454+02
 40.0 TO 45.0  6.6901+02  6.2168+01  6.3918+01  5.222 +01    0.91275  1.826 +02
 45.0 TO 50.0  6.8425+02  6.2283+01  7.1571+01  5.8471+01    0.91276  2.0416+02
 50.0 TO 55.0  7.0112+02  6.2399+01  7.9251+01  6.4745+01    0.91277  2.2574+02
 55.0 TO 60.0  7.156 +02  9.3772+01  8.696 +01  7.092 +01    0.91435  1.8161+02
 60.0 TO 65.0  7.357 +02  9.3947+01  9.4698+01  7.722 +01    0.91447  1.9745+02
 65.0 TO 70.0  7.6142+02  9.4122+01  1.0246+02  8.3553+01    0.91448  2.1333+02

   VEHICLE       ALPHA   PPCUM INPUT    ηPCUM     PCUT INPUT   BATTERY    BATTERY    BATTERY    BATTERY
    SPEED                   POWER     EFFICIENCY   CURRENT      POWER     VOLTAGE    CURRENT     LOSS
     MPH                     KW                     AMPS         KW          V         AMPS       KW

  0.0 TO  5.0    0.12258  6.5104+00    0.78143  2.7137+01  3.5716-01  2.399 +02  1.4887+00  1.9061-04
  5.0 TO 10.0    0.21531  1.1391+01    0.87579  4.7896+01  5.9929+00  2.3782+02  2.5199+01  5.4609-02
 10.0 TO 15.0    0.32710  1.725 +01    0.91847  7.3285+01  1.2609+01  2.3538+02  5.357 +01  2.468 -01
 15.0 TO 20.0    0.44272  2.3311+01    0.93998  1.0012+02  1.943 +01  2.3281+02  8.346 +01  5.9904-01
 20.0 TO 25.0    0.56056  2.9535+01    0.95284  1.2834+02  2.6424+01  2.3012+02  1.1482+02  1.1339+00
 25.0 TO 30.0    0.68382  3.6047+01    0.96152  1.5862+02  3.3687+01  2.2724+02  1.4823+02  1.8898+00
 30.0 TO 35.0    0.81371  4.2976+01    0.96785  1.9175+02  4.1394+01  2.2411+02  1.847 +02  2.9339+00
 35.0 TO 40.0    0.95314  5.0443+01    0.97273  2.2864+02  4.9717+01  2.2061+02  2.2535+02  4.3674+00
 40.0 TO 45.0    0.85875  5.3753+01    0.97147  2.4558+02  5.3753+01  2.1887+02  2.4558+02  5.1868+00
 45.0 TO 50.0    0.96911  5.9786+01    0.97473  2.7755+02  5.9986+01  2.1612+02  2.7755+02  6.6249+00
 50.0 TO 55.0    1.00000  6.6369+01    0.97552  2.8681+02  6.6369+01  2.314 +02  2.8681+02  7.0745+00
 55.0 TO 60.0    0.88661  7.2783+01    0.97439  3.4622+02  7.2783+01  2.1022+02  3.4622+02  1.0308+01
 60.0 TO 65.0    0.97575  7.9059+01    0.97674  3.816 +02  7.9059+01  2.0718+02  3.816 +02  1.2322+01
 65.0 TO 70.0    1.00000  8.5492+01    0.97731  3.9166+02  8.5492+01  2.1828+02  3.9166+02  1.3191+01
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PARALLEL EMT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .C86 CHMS
ETA(GC) =  .900

ACCELERATICN =  3.25 TO  4.25 MPH/SEC

   VEHICLE       TORQUE       MOTOR        MOTOR        POWER         MOTOR       TERMINAL
    SPEED      AT WHEEL       TORQUE       POWER        INPUT      EFFICIENCY     VOLTAGE
     MPH         FT-LB        FT-LB         HP           KW                          V

  0.0 TO  5.0  8.0117+02   6.126 +01   4.94   +00   6.6396+00     0.55481   2.3487+01
  5.0 TO 10.0  8.0346+02   6.1581+01   1.4897+01    1.3706+01     0.81053   4.8286+01
 10.0 TO 15.0  8.0738+02   6.2042+01   2.5015+01    2.1638+01     0.86205   7.5787+01
 15.0 TO 20.0  8.1291+02   6.2643+01   3.536 +01    2.9811+01     0.88459   1.0362+02
 20.0 TO 25.0  8.2CC7+C2   6.3386+01   4.6003+01    3.8C94+01     0.90050   1.3118+02
 25.0 TO 30.0  8.2884+02   6.427 +01   5.701 +01    4.6728+01     0.90978   1.5915+02
 30.0 TO 35.0  8.3923+02   6.5258+01   6.8453+01    5.5913+01     0.91294   1.8805+02
 35.0 TO 40.0  8.5124+02   6.6469+01   8.0401+01    6.5667+01     0.91301   2.1775+02
 40.0 TO 45.0  8.6487+C2   8.4775+01   8.7162+01    7.1113+01     0.91398   1.9705+02
 45.0 TO 50.0  8.8C11+02   8.4932+01   9.7596+01    7.9626+01     0.91398   2.2034+02
 50.0 TO 55.0  8.5658+02   8.5C89+01   1.0807+02    8.8171+01     0.91399   2.4365+02
 55.0 TO 60.0  9.1546+02   1.2787+02   1.1858+02    9.7404+01     0.90783   1.9467+02
 60.0 TO 65.0  9.3556+02   1.281 +02   1.2913+02    1.0607+02     0.90778   2.1172+02
 65.0 TO 70.0  9.5728+02   1.2834+02   1.3972+02    1.1478+02     0.90773   2.2878+02

   VEHICLE      ALPHA  P_PCUM INPUT   n_PCUM    PCUT INPUT   BATTERY     BATTERY     BATTERY     BATTERY
    SPEED                  POWER    EFFICIENCY   CURRENT      POWER      VOLTAGE     CURRENT      LOSS
     MPH                    KW                    AMPS         KW           V          AMPS        KW

  0.0 TO  5.0  0.12277  8.3019+00   0.79977   3.4706+01   2.1486+00   2.392 +02   8.9822+00   6.9386-03
  5.0 TO 10.0  0.22883  1.5353+01   0.89270   6.4953+01   9.9551+00   2.3637+02   4.2116+01   1.5254-01
 10.0 TO 15.0  C.34560  2.327 +01   0.92990   9.9819+01   1.8629+01   2.3312+C2   7.9913+01   5.492 -01
 15.0 TO 20.0  0.47555  3.1427+01   0.94858   1.3682+02   2.7547+01   2.2968+02   1.1993+02   1.237 +00
 20.0 TO 25.0  0.60463  3.9695+01   0.95967   1.7557+02   3.6584+01   2.2608+02   1.6182+02   2.2519+00
 25.0 TO 30.0  0.74054  4.8314+01   0.96718   2.1742+C2   4.5954+01   2.2221+02   2.068 +02   3.6779+C0
 30.0 TO 35.0  C.66708  5.7482+01   0.97270   2.6375+02   5.59   +01   2.1794+02   2.565 +02   5.6579+00
 35.0 TO 40.0  1.0CCC0  6.729 +01   0.97588   3.0157+02   6.6564+01   2.2313+02   2.9831+02   7.6532+00
 40.0 TO 45.0  0.96060  7.2862+01   0.97599   3.4666+02   7.2862+01   2.1018+02   3.4666+02   1.0334+01
 45.0 TO 50.0  1.C0000  8.1505+01   0.97694   3.6137+02   8.15C5+01   2.2554+02   3.6137+02   1.123 +01
 50.0 TO 55.0  1.C0000  9.025 +01   0.97695   3.6187+02   9.025 +01   2.494 +02   3.6187+02   1.1261+01
 55.0 TO 60.0  1.0C000  9.9594+01   0.97801   5.0034+C2   9.9594+01   1.9905+02   5.0034+02   2.1528+01
 60.0 TO 65.0  1.00000  1.0846+02   0.97801   5.0102+02   1.0846+02   2.1648+02   5.0102+02   2.1587+C1
 65.0 TO 70.0  1.00000  1.1736+02   0.97801   5.017 +02   1.1736+02   2.3392+02   5.017 +02   2.1646+01
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PARALLEL EHT
WITH GEARING
P(IC) = 11.75 HP
R(B) = .086 OHMS
ETA(GO) = .900

ACCELERATION = 4.25 TO 5.25 MPH/SEC

VEHICLE SPEED MPH	TORQUE AT WHEEL FT-LB	MOTOR TORQUE FT-LB	MOTOR POWER HP	POWER INPUT KW	MOTOR EFFICIENCY	TERMINAL VOLTAGE V
0.0 TO 5.0	5.9702+02	7.7968+01	6.2873+00	8.4021+00	0.55801	2.4755+01
5.0 TO 10.0	9.9932+02	7.8319+01	1.8947+01	1.7513+01	0.80673	5.1431+01
10.0 TO 15.0	1.0032+03	7.8811+01	3.1776+01	2.7543+01	0.86031	8.0518+01
15.0 TO 20.0	1.0087+03	7.9443+01	4.4844+01	3.7766+01	0.88498	1.0982+02
20.0 TO 25.0	1.0159+03	8.0216+01	5.8217+01	4.8176+01	0.90113	1.3903+02
25.0 TO 30.0	1.0247+03	8.1132+01	7.1967+01	5.8831+01	0.91219	1.6838+02
30.0 TO 35.0	1.035 +03	8.2191+01	8.6162+01	7.0308+01	0.91384	1.9932+02
35.0 TO 40.0	1.0471+03	8.3393+01	1.0087+02	8.2306+01	0.91391	2.3086+02
40.0 TO 45.0	1.0607+03	1.0738+02	1.104 +02	9.0251+01	0.91222	2.0725+02
45.0 TO 50.0	1.0759+03	1.0758+02	1.2362+02	1.0106+02	0.91217	2.3173+02
50.0 TO 55.0	1.0528+03	1.0778+02	1.3688+02	1.1191+02	0.91213	2.5623+02
55.0 TO 60.0	1.1113+03	1.6197+02	1.502 +02	1.2393+02	0.90379	2.0684+02
60.0 TO 65.0	1.1314+03	1.6227+02	1.6357+02	1.3495+02	0.90379	2.2491+02
65.0 TO 70.0	1.1531+03	1.6257+02	1.7698+02	1.4602+02	0.90379	2.43 +02

VEHICLE SPEED MPH	ALPHA	P_{PCUM} INPUT POWER KW	η_{PCUM} EFFICIENCY	PCUT INPUT CURRENT AMPS	BATTERY POWER KW	BATTERY VOLTAGE V	BATTERY CURRENT AMPS	BATTERY LOSS KW
0.0 TO 5.0	0.12718	1.0294+01	0.81615	4.3167+01	4.1414+00	2.3848+02	1.7365+01	2.5934-02
5.0 TO 10.0	0.24233	1.9382+01	0.90359	8.2521+01	1.3984+01	2.3487+02	5.9538+01	3.0485-01
10.0 TO 15.0	0.37224	2.9385+01	0.93730	1.2733+02	2.4744+01	2.3077+02	1.0722+02	9.8874-01
15.0 TO 20.0	0.50832	3.9602+01	0.95415	1.7489+02	3.5721+01	2.2643+02	1.5775+02	2.1403+00
20.0 TO 25.0	0.65002	4.9964+01	0.96420	2.2523+02	4.6853+01	2.2183+02	2.1121+02	3.8364+00
25.0 TO 30.0	0.75550	6.0591+01	0.97095	2.7934+02	5.8231+01	2.1691+02	2.6846+02	6.1981+00
30.0 TO 35.0	0.96638	7.2035+01	0.97601	3.4087+02	7.0454+01	2.1132+02	3.3339+02	9.5586+00
35.0 TO 40.0	1.00000	8.4254+01	0.97688	3.5652+02	8.3527+01	2.3632+02	3.5345+02	1.0743+01
40.0 TO 45.0	1.00000	9.231 +01	0.97768	4.3546+02	9.231 +01	2.1198+02	4.3546+02	1.6307+01
45.0 TO 50.0	1.00000	1.0336+02	0.97769	4.3611+02	1.0336+02	2.3702+02	4.3611+02	1.6356+01
50.0 TO 55.0	1.00000	1.1446+02	0.97769	4.3676+02	1.1446+02	2.6208+02	4.3676+02	1.6405+01
55.0 TO 60.0	1.00000	1.267 +02	0.97812	5.9915+02	1.267 +02	2.1147+02	5.9915+02	3.0872+01
60.0 TO 65.0	1.00000	1.3797+02	0.97812	6.0003+02	1.3797+02	2.2994+02	6.0003+02	3.0963+01
65.0 TO 70.0	1.00000	1.4929+02	0.97812	6.0092+02	1.4929+02	2.4844+02	6.0092+02	3.1054+01

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PARALLEL EPT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .066 OHMS
ETA(GC) =  .900

ACCELERATION =  5.25 TO  6.25 MPH/SEC


  VEHICLE      TORQUE       MOTOR        MOTOR        POWER        MOTOR      TERMINAL
   SPEED      AT WHEEL      TORQUE       POWER        INPUT     EFFICIENCY     VOLTAGE
    MPH        FT-LB        FT-LB         HP           KW                        V


  0.0 TO  5.0  1.1528+03  9.4676+01  7.6346+00  1.0147+01    0.56106  2.5787+01
  5.0 TO 10.0  1.1951+03  9.5058+01  2.2996+01  2.1352+01    0.80309  5.409 +01
 10.0 TO 15.0  1.1991+03  9.556 +01  3.8537+01  3.3468+01    0.85865  8.4411+01
 15.0 TO 20.0  1.2046+03  9.6243+01  5.4327+01  4.5753+01    0.88544  1.1475+02
 20.0 TO 25.0  1.2117+03  9.7047+01  7.0432+01  5.825 +01    0.90166  1.4513+02
 25.0 TO 30.0  1.2205+03  9.7993+01  8.6924+01  7.0911+01    0.91409  1.753 +02
 30.0 TO 35.0  1.2309+03  9.9083+01  1.0387+02  8.4737+01    0.91407  2.0763+02
 35.0 TO 40.0  1.2429+03  1.0031+02  1.2134+02  9.9021+01    0.91379  2.4023+02
 40.0 TO 45.0  1.2565+03  1.2598+02  1.3364+02  1.0582+02    0.90741  2.1688+02
 45.0 TO 50.0  1.2718+03  1.3022+02  1.4964+02  1.2298+02    0.90737  2.4252+02
 50.0 TO 55.0  1.2866+03  1.3047+02  1.657 +02  1.3618+02    0.90732  2.682 +02
 55.0 TO 60.0  1.3071+03  1.9606+02  1.8182+02  1.5002+02    0.90379  2.0624+02
 60.0 TO 65.0  1.3272+03  1.5643+02  1.98  +02  1.6337+02    0.90379  2.2442+02
 65.0 TO 70.0  1.349 +03  1.968 +02  2.1424+02  1.7676+02    0.90379  2.4264+02

  VEHICLE      ALPHA  PPCUM INPUT   ηPCUM     PCUT INPUT  BATTERY    BATTERY    BATTERY    BATTERY
   SPEED                POWER     EFFICIENCY   CURRENT     POWER     VOLTAGE    CURRENT     LOSS
    MPH                  KW                     AMPS        KW          V         AMPS       KW


  0.0 TO  5.0  0.13113  1.2268+01   0.82712  5.16  +01  6.1147+00  2.3775+02  2.5719+01  5.6886-02
  5.0 TO 10.0  0.25446  2.3439+01   0.91096  1.0045+02  1.8041+01  2.3334+02  7.7317+01  5.1411-01
 10.0 TO 15.0  0.39226  3.5518+01   0.94228  1.5552+02  3.0877+01  2.2837+02  1.352 +02  1.5722+00
 15.0 TO 20.0  0.53704  4.7764+01   0.95788  2.1411+02  4.3884+01  2.2308+02  1.9671+02  3.328 +00
 20.0 TO 25.0  0.69016  6.0221+01   0.96726  2.77  +02  5.711 +01  2.174 +02  2.6269+02  5.9344+00
 25.0 TO 30.0  0.85217  7.2839+01   0.97352  3.447 +02  7.0479+01  2.1131+02  3.3353+02  9.5667+00
 30.0 TO 35.0  1.00000  8.669 +01   0.97747  4.081 +02  8.5109+01  2.1242+02  4.0066+02  1.3805+01
 35.0 TO 40.0  1.00000  1.013 +02   0.97750  4.1219+02  1.0057+02  2.4575+02  4.0924+02  1.4402+01
 40.0 TO 45.0  1.00000  1.1229+02   0.97803  5.0641+02  1.1229+02  2.2175+02  5.0641+02  2.2054+01
 45.0 TO 50.0  1.00000  1.2574+02   0.97803  5.071 +02  1.2574+02  2.4797+02  5.071 +02  2.2114+01
 50.0 TO 55.0  1.00000  1.3924+02   0.97803  5.0779+02  1.3924+02  2.7422+02  5.0779+02  2.2175+01
 55.0 TO 60.0  1.00000  1.5342+02   0.97781  7.2739+02  1.5342+02  2.1092+02  7.2739+02  4.5502+01
 60.0 TO 65.0  1.00000  1.6707+02   0.97780  7.2795+02  1.6707+02  2.2951+02  7.2795+02  4.5572+01
 65.0 TO 70.0  0.00000  0.    +00   1.00000  0.    +00  0.    +00  0.    +00  0.    +00  0.    +00
```

```
PARALLEL EMT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .CE6 CHMS
ETA(GC) =  .900

ACCELERATICN =  6.25 TO  7.25 MPH/SEC

   VEHICLE      TCRQLE       MOTOR       MOTOR        POWER       MOTOR       TERMINAL
    SPEED      AT WHEEL      TURQUE      POWER        INPUT     EFFICIENCY    VOLTAGE
     MPH         FT-LB       FT-LB        HP           KW                        V

  0.0 TO  5.0  1.3EE7+C3   1.1138+02   8.982 +00   1.2424+01   0.53909    2.7698+01
  5.0 TO 10.0  1.391 +03   1.1179+02   2.7045+01   2.5487+01   0.79130    5.665 +01
 10.0 TO 15.0  1.3949+03   1.1234+02   4.5299+01   3.9656+01   0.85180    8.7791+01
 15.0 TO 20.0  1.4004+03   1.1304+02   6.381 +01   5.3987+01   0.88138    1.1891+02
 20.0 TO 25.0  1.4C76+03   1.1387+02   8.2647+01   6.8551+01   0.89903    1.5009+02
 25.0 TO 30.0  1.4164+03   1.1465+02   1.0168+02   8.3447+01   0.91042    1.8144+02
 30.0 TO 35.0  1.4268+C3   1.1597+02   1.2157+02   9.9593+01   0.91031    2.1483+02
 35.0 TO 40.0  1.4388+03   1.1724+02   1.4181+02   1.162 +02   0.91003    2.4845+02
 40.0 TO 45.0  1.4524+C3   1.5259+02   1.5689+02   1.2944+02   0.90379    2.2642+02
 45.0 TO 50.0  1.4676+03   1.5287+02   1.7567+02   1.4494+02   0.90379    2.5316+02
 50.0 TO 55.0  1.4845+C3   1.5316+02   1.9452+02   1.6049+02   0.90379    2.7993+02
 55.0 TO 60.0  1.503 +03   2.3016+02   2.1344+02   1.7611+02   0.90379    2.2222+02
 60.0 TO 65.0  1.5231+03   2.3059+02   2.3244+02   1.9178+02   0.90379    2.4163+02
 65.0 TO 70.0  1.5448+03   2.3102+02   2.515 +02   2.0751+02   0.90379    2.6106+02

   VEHICLE       ALPHA    P        INPUT    n            PCUT INPUT   BATTERY     BATTERY     BATTERY     BATTERY
    SPEED                  PCUM              PCUM        CURRENT      POWER       VOLTAGE     CURRENT     LOSS
     MPH                    POWER        EFFICIENCY       AMPS         KW           V           AMPS        KW
                             KW

  0.0 TO  5.0  0.13916  1.4785+01   0.84029   6.2423+01   8.6323+00   2.3686+02   3.6444+01   1.1422-01
  5.0 TO 10.0  0.26673  2.7802+01   0.91670   1.2    +02  2.2404+01   2.3167+02   9.6706+01   8.0428-01
 10.0 TO 15.0  0.41101  4.1921+01   0.94597   1.8565+C2   3.728 +01   2.2579+02   1.651 +02   2.3443+0C
 15.0 TO 20.0  0.56356  5.6198+01   0.96064   2.5603+02   5.2318+01   2.195 +02   2.3835+02   4.8857+CC
 20.0 TO 25.0  0.72797  7.0705+01   0.96953   3.3247+C2   6.7594+01   2.1266+02   3.1785+02   8.6882+00
 25.0 TO 30.0  C.9C669  8.5538+01   0.97555   4.17   +02  8.3178+01   2.0512+02   4.055 +02   1.414 +01
 30.0 TO 35.0  1.000C0  1.0184+02   0.97785   4.6358+02   1.0026+02   2.197 +02   4.5638+02   1.7912+01
 35.0 TO 40.0  1.0C000  1.1883+02   0.97788   4.6772+02   1.181 +02   2.5407+02   4.6486+02   1.8584+C1
 40.0 TO 45.0  1.00000  1.3234+02   0.97812   5.717 +02   1.3234+02   2.3148+02   5.717 +02   2.8108+01
 45.0 TO 50.0  1.00CCC  1.4818+02   0.97812   5.7253+02   1.4818+02   2.5883+02   5.7253+02   2.819 +C1
 50.0 TO 55.0  1.00000  1.64C8+02   0.97812   5.7336+02   1.64C8+02   2.8619+02   5.7336+02   2.8271+C1
 55.0 TO 60.0  0.C0000  0.    +00   1.00000   0.    +00   0.    +00   0.    +00   0.    +00   0.    +CO
 60.0 TO 65.0  0.00000  0.    +00   1.00000   0.    +00   0.    +00   0.    +00   0.    +00   0.    +00
 65.0 TO 70.0  0.CCCC0  0.    +00   1.00000   0.    +00   0.    +00   0.    +00   0.    +00   0.    +00
```

20

```
PARALLEL EMT
WITH GEARING
P(IC) =  11.75 HP
R(B) =  .086 OHMS
ETA(GG) =  .900

ACCELERATION =  7.25 TO  8.25 MPH/SEC

  VEHICLE      TORQUE      MOTOR      MOTOR       POWER      MOTOR      TERMINAL
   SPEED      AT WHEEL     TORQUE     POWER       INPUT    EFFICIENCY   VOLTAGE
    MPH        FT-LB       FT-LB       HP          KW                      V


 0.0 TO  5.0  1.5846+03  1.2809+02  1.0329+01  1.4956+01    0.51498  2.9855+01
 5.0 TO 10.0  1.5869+03  1.2853+02  3.1095+01  2.9754+01    0.77930  5.9243+01
10.0 TO 15.0  1.5508+03  1.2911+02  5.206 +01  4.5942+01    0.84500  9.1171+01
15.0 TO 20.0  1.5563+03  1.2984+02  7.3293+01  6.2287+01    0.87746  1.231 +02
20.0 TO 25.0  1.6035+03  1.307 +02  9.4862+01  7.6898+01    0.89658  1.5516+02
25.0 TO 30.0  1.6122+03  1.3171+02  1.1683+02  9.6058+01    0.90701  1.8784+02
30.0 TO 35.0  1.6226+03  1.3266+02  1.3928+02  1.1453+02    0.90686  2.2254+02
35.0 TO 40.0  1.6346+03  1.3416+02  1.6228+02  1.3348+02    0.90660  2.575 +02
40.0 TO 45.0  1.6483+03  1.752 +02  1.8013+02  1.4862+02    0.90379  2.3036+02
45.0 TO 50.0  1.6635+03  1.7552+02  2.017 +02  1.6641+02    0.90379  2.5738+02
50.0 TO 55.0  1.6804+03  1.7565+02  2.2334+02  1.8427+02    0.90379  2.8437+02
55.0 TO 60.0  1.6588+03  2.6427+02  2.4507+02  2.022 +02    0.90379  2.2828+02
60.0 TO 65.0  1.7189+03  2.6476+02  2.6688+02  2.2019+02    0.90379  2.4822+02
65.0 TO 70.0  1.7407+03  2.6525+02  2.8876+02  2.3825+02    0.90379  2.6818+02

  VEHICLE        ALPHA  P_PCUM INPUT     η_PCUM     PCUT INPUT   BATTERY     BATTERY     BATTERY     BATTERY
   SPEED                   POWER       EFFICIENCY    CURRENT      POWER      VOLTAGE     CURRENT      LOSS
    MPH                     KW                        AMPS         KW           V          AMPS        KW


 0.0 TO  5.0     0.14658  1.7554+01    0.85202  7.4434+01  1.1401+01  2.3583+02  4.8343+01  2.0098-01
 5.0 TO 10.0     0.27563  3.2293+01    0.92138  1.4044+02  2.6894+01  2.2993+02  1.1696+02  1.1765+00
10.0 TO 15.0     0.43058  4.6413+01    0.94895  2.1697+02  4.3772+01  2.2312+02  1.9617+02  3.3098+00
15.0 TO 20.0     0.59250  6.4686+01    0.96291  2.998 +02  6.0806+01  2.1576+02  2.8182+02  6.8302+00
20.0 TO 25.0     0.76921  8.1217+01    0.97144  3.9113+02  7.8106+01  2.0765+02  3.7614+02  1.2167+01
25.0 TO 30.0     0.96665  9.8285+01    0.97733  4.9533+02  9.5926+01  1.9842+02  4.8344+02  2.0099+01
30.0 TO 35.0     1.00000  1.171 +02    0.97805  5.1467+02  1.1552+02  2.2753+02  5.0772+02  2.2168+01
35.0 TO 40.0     1.00000  1.3647+02    0.97806  5.1838+02  1.3574+02  2.6327+02  5.1563+02  2.2864+01
40.0 TO 45.0     1.00000  1.5195+02    0.97806  6.4518+02  1.5195+02  2.3552+02  6.4518+02  3.5798+01
45.0 TO 50.0     0.00000  0.     +00   1.00000  0.     +00  0.     +00  0.     +00  0.     +00  0.     +00
50.0 TO 55.0     0.00000  0.     +00   1.00000  0.     +00  0.     +00  0.     +00  0.     +00  0.     +00
55.0 TO 60.0     0.00000  0.     +00   1.00000  0.     +00  0.     +00  0.     +00  0.     +00  0.     +00
60.0 TO 65.0     0.00000  0.     +00   1.00000  0.     +00  0.     +00  0.     +00  0.     +00  0.     +00
65.0 TO 70.0     0.00000  0.     +00   1.00000  0.     +00  0.     +00  0.     +00  0.     +00  0.     +00
```

APPENDIX H

Design of Traction Motor PCU for Size and Cost Estimates

There is a large number of components in each of the power control units each of which must be identified and specified so that potential vendors can provide "best" cost data for assembling units in high volume.

The series and parallel hybrids both contain motor PCUs which are rated for 600 amperes for estimating purposes. (The use of variable gearing was shown in the simulation to give higher LA-4 efficiency; also lower cost solid state and commutating devices can be used in this system.) The following presents a condensed design and costing exercise directed at estimating the size and cost of such a unit.

600 Ampere Chopper for Motor PCU

The PCU under consideration is shown in the schematic diagram of Figure E-1.

Rating - 54 kw at 240 VDC maximum steady state load (design for series system)

Commutation capability - 240A nominal, 600A maximum, 144 KVA

Forced air cooling provided by external fans

Chopper frequency - 1 KHZ

Power SCR, SCR_1 - equivalent to GE C395M; turn-off time 15 microsec.

Power SCR dissipation 1.5 V x 240 = 360 watts (@ 54 kw)

Commutation SCR (SCR_C) - equivalent to GE C364M; turn-off time 10 microsec.

Commutation capacitor - C_c

$$C_c = \frac{It}{V} = \frac{600\text{x}15\text{x}10^{-6}}{240\text{x}.9} = 42\ \mu\text{fd}$$

Maximum voltage swing - 504 volts

Require 2-20 μfd capacitors equivalent to GE 28F5137 (4.6" x 2.8" x 5.2", weighing 3.5 pounds each)

Capacitors will occupy about 170 in^3 and with mounting brackets will weigh about 10 pounds.

Commutation inductor - L_c

Chose 6 μH inductor

$$t = \pi\sqrt{LC} = \pi\sqrt{6\text{x}10^{-6}\text{x}42\text{x}10^{-6}} = 50.4\ \mu\text{s},\ (\sim 5\%\ \text{of chopper period})$$

Commutation impedance - Z

$$Z = \sqrt{L/C} = \sqrt{6/40} = 0.39$$

Commutation current - I_c

$$I_{c\ peak} = 680 \text{ amperes}$$

$$I_{c\ rms} = 680\sqrt{\frac{50.4}{2000}} = 108 \text{ amperes (rms)}$$

Commutation linear inductor - 6 μH air type

$$\frac{6}{17} = \left(\frac{N}{11}\right)^2$$

$$N = \sqrt{\frac{121\text{x}6}{17}} = 6.55 \approx 7 \text{ turns}$$

Wire size @500 cm/A is #3 AWG; 8 feet only

Weight of chopper - 1.27 pounds

Inductor resistance - $1.58\text{x}10^{-3}$ ohms

Additional weight for structure, mounting brackets, etc. - 2.0 pounds

Total inductor assembly - 3.3 pounds

Power SCR Assembly

The power SCR dissipates 360 watts on a steady state basis; allowing a case temperature of 80^oC and ambient air at 40^oC leads to the selection of a heat sink having 270 in^3 volume, weighing 5 pounds with the SCR.

Other Semiconductors

Commutating SCR (SCR_C) and heat sink	4.0 pounds
Two flyback rectifiers and heat sinks	5.0 pounds
Precharge, charging and polarizing rectifiers	2 pounds
All semiconductors with respective heat sinks and mounting brackets	16 pounds
Commutation and filter capacitors	10 pounds
Commutation linear inductor and mounting system	3.3 pounds
Saturable reactor and mounting system	2.0 pounds

Switches (two)--15.0 pounds
Fusing and protection network------------------------10 pounds
Logic module and current sensors---------------------15 pounds
Total electric system weight----------------------71.3 pounds
Structural panel, lightweight honeycomb-----------16.8 pounds
Total PCU weight------------------------------88.1 pounds

Size: 2.3 cubic feet (10"x20"x20")

Parts and OEM Price List for Motor PCU

PCU Specification: 600 amperes, 240 VDC, 1 KHZ using 15 μsec turn-off SCRs

Symbol	Manufacturer's Designation*	OEM Cost ($)
(SCRs and Heat Sinks)		
SCR_1	C395M	20
SCR_2	C364M	10
SCRD	C390M	17
SCRR	C390M	17
(Rectifiers & Heat Sinks)		
CRF	A396M	5
CR1	A396M	5
CR2	A396M	5
CRD	A390M	4
CRR	A390M	4
(Commutation Elements)		
C_c (2 req'd)	28F5125(40μfd)	10
L_c	6μhg (9 A_{rms})	2
SR	4.5 mV-sec (104 A_{rms})	2
(Fuses)		
Fx		10
Logic & Ancillaries	(176 discrete elements)	33
Structural		5
	Total	$149

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*General Electric designation for reference only.

Parts and OEM Price List for Alternator PCU for Parallel Hybrid System

PCU Specification: 100 amperes, 240 VDC, 1 KHZ using 10 μsec turn-off SCRs

Symbol	Manufacturer's Designation*	OEM Cost ($)
(SCRs & Heat Sinks)		
SCR_1	C364	10
SCR_2	C364	10
(Rectifiers & Heat Sinks)		
CRF	SC5F6	4
CR1	SC5F6	4
CR2	SC5F6	4
CR(Bridge)	SC5F6	12
(Commutation Elements)		
C_c	28F5122 (5μfd)	2
L_c	13 μhg (16 A_{rms})	2
S_R	2.5 mV-sec (12 A_{rms})	2
(Fuses)		
F_x		10
Logic & Ancillaries	(166 discrete elements)	31
Structural		
	Total	$131

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*General Electric designation for reference only

TABLE I-1

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (^{o}F)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During			
					ppm In	ppm Out		Adsorption In	Adsorption Out	Desorption In	Desorption Out
Activated Carbon Pittsburgh A.C. Co. Type BPL "as received" (1st Cold Start)	4x6 mesh	270	0.5	110	7500	1400	81	1353	444		
			1.0	135	2350	650	72				
			1.5	170	1300	360	72				
			2.0	190	830	265	68				
			3.0	220	610	235	61				
			4.0	310	500	240	52				
			4.5	-	450	350	22				
			5.0	390	530	430	19				
			6.0*	430*	525	465	12				
			8.0	495	490	550	-12			505	610
			10.0	555	470	620	-32				
			12.0	605	530	710	-34				
			14.0	640	520	690	-33				
			16.0	670	510	630	-24				
			18.0	700	510	560	-10				
			20.0	720	500	500	0				
2nd Cold Start		270 (no measurable attrition)	0.5	105	4500	1200	77	940	385		
			1.0	130	2250	600	73				
			1.5	155	1100	270	75				
			2.0	170	710	235	67				
			3.0	230	550	215	61				
			4.0	315	425	245	42				
			5.0	380	420	280	33				
			7.0*	465*	450	400	11				
			8.0	500	460	500	-9			460	570
			10.0	550	460	580	-26				
			12.0	610	460	650	-41				
			14.0	650	460	650	-41				
			16.0	685	460	610	-33				
			18.0	715	460	536	-16				
			20.5	740	460	470	-2				

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During			
					ppm In	ppm Out		Adsorption In	Adsorption Out	Desorption In	Desorption Out
3rd Cold Start		270 (no measurable attrition)	0.5	105	6600	1250	81	1261	384		
			1.0	130	2150	600	72				
			1.5	-	900	250	72				
			2.0	175	620	210	66				
			3.0	260	480	215	55				
			4.0	340	370	255	31				
			5.0*	385*	320	295	8				
			6.0	420	315	340	-8			455	578
			8.0	510	320	430	-34				
			10.0	570	375	550	-47				
			12.0	610	460	670	-46				
			14.0	660	540	725	-34				
			16.0	685	560	695	-24				
			18.0	720	500	570	-14				
			19.5	730	500	520	-4				
4th Cold Start		270 (no measurable attrition)	0.5	105	7200	950	87	1440	386		
			1.0	130	2400	630	74				
			1.5	155	1100	280	75				
			2.0	175	750	230	69				
			3.0	240	590	235	60				
			4.0	320	460	290	37				
			5.0*	380*	425	360	15				
			6.0	425	385	410	-7			493	635
			8.0	490	420	500	-19				
			10.0	555	430	640	-49				
			12.0	610	500	755	-51				
			14.0	650	510	740	-45				
			16.0	680	510	685	-34				
			18.0	710	510	635	-24				
			20.5	735	525	600	-14				

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval ppm In	ppm Out	Holdup	Ave. Exhaust HC Concentrations (ppm) During Adsorption In	Adsorption Out	Desorption In	Desorption Out
5th Cold Start**			0.5	115	7000	1350	81				
			1.0	140	2600	1000	62				
			1.5	155	1000	550	45				
			2.0	170	750	570	30				
			2.5*	195*	600	510	16				
			3.0	225	500	600	-20				
			3.5	265	480	750	-56				
			4.0	320	425	1050	-146				
			5.0	385	370	1800	-385				
			6.0	415	340	2700	-690				
			8.0	480	340	3100	-810				
			10.0	540	440	2950	-570				
			12.0	595	480	2600	-440				
			14.0	640	510	2100	-310				
			16.0	670	520	1600	-210				
			18.0	695	530	1350	-154				
			19.0	710	535	1100	-87				
			26.0	-	530	680	-28				

**Prior to this start the accumulator was subjected to four 30-sec. by HC rich cold starts. Estimated total HC retention during these loadings: 16 grams.

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval ppm In	ppm Out	Holdup	Ave. Exhaust HC Concentrations (ppm) During Adsorption In	Adsorption Out	Desorption In	Desorption Out
Nuclear (Activated Carbon) Westvaco WV-H Type	6x16 mesh	202	0.5	105	9000	800	91				
			1.0	145	2450	610	75				
			1.5	170	1350	280	79				
			2.0	190	780	235	70				
			2.5	215	630	220	65	1800	373		
			3.0	245	560	225	60				
			3.5	-	520	260	50				
"as received" (1st Cold Start)			4.0	330	460	330	28				
			4.5*	360*	440	400	9				
			5.0	380	410	410	0				
			5.5	-	380	415	-9				
			6.0	420	380	390	-3			396	421
			8.0	480	380	418	-8				
			10.0	535	420	440	-5				
			12.0	580	380	380	0				
			14.0	615	420+20	420+20	0				
			20.0	690	420±20	420±20	0				
2nd Cold Start	6x16 mesh or smaller due to attrition	190**	0.5	105	5100	800	84				
			1.0	135	2300	615	73				
			1.5	155	1300	300	77				
			2.0	175	820	285	65				
			2.5	195	750	280	63	1324	432		
			3.0	230	660	305	54				
			3.5	-	620	370	40				
			4.0	300	600	440	27				
			4.5	-	560	460	18				
			5.0	345	530	465	12				
			5.5	-	510	510	0				
			6.0	400	510	520	-2				
			8.0	470	490	540	-10				
			10.0	520	450	540	-20			475	537
			12.0	580	470	550	-17				
			14.0	615	480	520	-8				
			14.0	-	400+30	400+30	0				
			20.0	690	400±30	400±30	0				

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (^{o}F)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During			
								Adsorption		Desorption	
					ppm In	ppm Out		In	Out	In	Out
Charcoal (coconut shell) Barneby-Cheney MI 8588 "as received" (1st Cold Start)	10x20 mesh	171	0.5	100	7500	1000	85	1256	365		
			1.0	125	3200	650	80				
			1.5	155	1300	250	80				
			2.0	170	960	225	77				
			2.5	180	910	205	77				
			3.0	190	750	195	74				
			3.5	210	675	195	71				
			4.0	230	630	200	68				
			4.5	260	580	215	63				
			5.0	320	535	270	50				
			5.5	370	510	315	38				
			6.0	390	510	360	30				
			8.0*	470*	510	440	14				
			10.0	530	510	480	6				
				-	480+10	480+10	0				
			20.0	700	480±10	480±10	0				
2nd Cold Start	10x20 mesh or smaller due to attrition	150**	0.5	105	5900	750	87	1170	393		
			1.0	140	2500	650	74				
			1.5	160	1300	275	79				
			2.0	175	830	265	68				
			3.0	230	660	255	61				
			3.5	265	545	310	43				
			4.5	310	510	360	29				
			6.0*	390*	480	420	13				
			8.0	465	455	540	-20			452	528
			10.0	520	460	550	-20				
			12.0	580	440	495	-13				
			14.0	615	430	430	0				
				-	400+10	400+10	0				
			20.0	705	400±10	400±10	0				

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During			
								Adsorption		Desorption	
					ppm In	ppm Out		In	Out	In	Out
Charcoal 3rd Cold Start	10x20 mesh or smaller due to attrition	130**	0.5	105	2700	900	67	843	410		
			1.0	135	1550	660	58				
			1.5	150	840	330	61				
			2.0	175	580	245	58				
			2.5	190	530	240	55				
			3.0	225	520	280	46				
			3.5	250	520	315	40				
			4.0	280	490	340	30				
			4.5	320	460	380	17				
			5.0*	360*	470	460	2				
			6.0	400	430	515	-20			437	528
			8.0	475	410	560	-36				
			10.0	530	420	555	-32				
			12.0	585	460	525	-14				
			14.0	615	460	480	-4				
			16.0	660	425	425	0				
			20.0	710	430±10	430±10	0				

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During			
								Adsorption		Desorption	
					ppm In	ppm Out		In	Out	In	Out
Molecular Sieve Linde 13X	1/8x1/16" cylinders	314	0.5	110	3200	900	72	2100	1093		
			1.0	160	2150	1400	35				
			1.5*	235*	950	980	-3			464	485
"as received" (1st Cold Start)			2.0	275	720	770	-7				
			2.5	305	620	680	-10				
			3.0	325	540	600	-11				
			3.5	345	480	530	-11				
			4.0	355	480	520	-8				
			4.5	370	470	490	-4				
			5.0	385	450	470	-4				
			5.5	395	450	470	-4				
			6.0	410	470	470	0				
			8.0	455	500	500	0				
			10.0	520	470	470	0				
			12.0	565	360	390	-8				
			14.0	620	400	420	-5				
			16.0	670	375	375	0				
			↓ 20.0	740	↓	↓	↓				
2nd Cold Start		314 (no measurable attrition)	0.5	130	4700	1500	68	3525	1700		
			1.0	210	2350	1900	19				
			1.5*	255*	1050	1400	-33			500	575
			2.0	270	800	1100	-38				
			2.5	305	640	840	-31				
			3.0	315	600	710	-18				
			3.5	330	500	635	-27				
			4.0	335	440	560	-27				
			4.5	350	440	535	-21				
			5.0	370	480	540	-13				
			5.5	-	480	525	-9				
			6.0	395	455	495	-9				
			8.0	440	420	440	-5				
			10.0	495	420	440	-5				
			12.0	555	420	450	-7				
			14.0	615	500	530	-6				
			16.0	650	530	530	0				
			↓ 20.0	710	↓	↓					

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval ppm In	ppm Out	Holdup	Ave. Exhaust HC Concentrations (ppm) During Adsorption In	Adsorption Out	Desorption In	Desorption Out
Molecular Sieve Davidson 10A-13X "as received" (1st Cold Start)	1/16" spheres	350	0.5	95	4500	850	81				
			1.0	125	2050	1100	46				
			1.5	175	930	800	14				
			2.0	200	700	600	14	1555	720		
			2.5	240	620	510	17				
			3.0	280	530	460	13				
			3.5*	310*	440	440	0				
			4.0	330	440	470	-9				
			4.5	-	440	470	-9				
			5.0	365	380	420	-10				
			5.5	-	410	430	-7			406	437
			6.0	405	380	420	-10				
			8.0	445	400	430	-7				
			10.0	505	470	470	0				
			20.0	720	↓	↓	↓				
2nd Cold Start (Engine cooled for 4 hours)		350 (attrition <3% in 2 runs)	0.5	95	5000	940	81				
			1.0	125	2250	1250	44	2300	985		
			1.5	160	1100	900	18				
			2.0*	195*	850	850	0				
			2.5	225	760	800	-5				
			3.0	250	660	720	-9				
			3.5	260	570	680	-19				
			4.0	270	510	640	-25				
			4.5	-	510	640	-25				
			5.0	300	510	620	-21			520	593
			5.5	-	440	540	-23				
			6.0	320	440	510	-16				
			8.0	370	460	490	-7				
			10.0	430	440	440	0				
			20.0	670							

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (^oF)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During Adsorption		Ave. Exhaust HC Concentrations (ppm) During Desorption	
					ppm In	Out ppm		In	Out	In	Out
Silica Gel Davidson Grade 40	6x12 mesh	355									
"as received"	Test was aborted before completion due to extremely poor engine start										
2nd Cold Start (Engine cooled overnight)		340**	0.5	105	8500	1500	82	3933	1350		
			1.0	145	2150	1500	30				
			1.5*	175*	1150	1050	9				
			2.0	195	760	800	-5			456	585
			2.5	-	650	710	-9				
			3.0	220	575	655	-14				
			3.5	-	490	590	-20				
			4.0	250	435	550	-26				
			4.5	-	450	550	-22				
			5.0	280	400	530	-32				
			5.5	-	425	540	-27				
			6.0	330	420	550	-31				
			8.0	455	400	600	-49				
			10.0	505	450	660	-47				
			12.0	555	450	580	-28				
			14.0	595	400	445	-11				
			16.0 ↓	630	420 ↓	420 ↓	0				
			20.0	690							

TABLE I-1 (cont'd)

HYDROCARBON ACCUMULATOR MATERIALS SCREENING DATA

Accumulator Material	Particle Size	Bed Weight (grams)	Time From Engine Start-Up (min.)	Ave. Bed Temp. (°F)	Ave. Exhaust HC Concentrations for Preceding Time Interval		Holdup	Ave. Exhaust HC Concentrations (ppm) During			
					ppm In	Out ppm		Adsorption In	Adsorption Out	Desorption In	Desorption Out
Silica Gel 3rd Cold Start (Engine cooled for 3 hours)		325** (total attrition in 3 runs, 45 grams)	0.5	110	3500	1075	69	2800	1263		
			1.0	140	2100	1450	31				
			1.5*	170*	1000	1000	0				
			2.0	190	760	850	-12			510	598
			2.5	200	675	800	-18				
			3.0	220	580	710	-22				
			3.5	-	510	630	-25				
			4.0	245	500	580	-16				
			4.5	-	490	560	-14				
			5.0	270	480	540	-12				
			6.0	310	420	480	-14				
			8.0	410	380	510	-34				
			10.0	510	470	660	-40				
			12.0	570	530	670	-26				
			14.0	615	550	620	-13				
			16.0	635	530	580	-10				
			18.0	665	530	550	-4				
			20.0	695	520	535	-3				
Activated Alumina Harshaw "as received" (only one test was performed with this material because of the very low "cross-over" temperature)	1/8x1/8" cylinders	435	0.5	110	8000	3000	63	5125	2675		
			1.0*	140*	2250	2350	-4				
			1.5	175	2000	2100	-5			892	1014
			2.0	195	900	1075	-20				
			3.0	230	590	780	-32				
			4.0	245	450	560	-25				
			5.0	290	400	460	-15				
			6.0	330	580	580	0				
			↓ 20.0	700	↓	↓	↓				

APPENDIX J

Determination of Stoichiometric Mixture Ratio

A measure of the stoichiometric mixture ratio is necessary so that catalyst conversion data can be interpreted. For rich mixtures the conversion of NO, HC and CO are limited by the chemical balance of oxidants and reductants. On the lean side, HC and CO conversion can be complete; NO conversion depends on the reaction selectivity of NO and O_2.

The air-fuel ratio at which the combustion equation could procede to completion is solely a function of the carbon/hydrogen composition of the fuel. There are several ways which the stoichiometric air-fuel ratio can be determined; each method has limitations which are described below.

Stoichiometric Air-Fuel Ratio Calculated from Fuel Composition

The fuel used in the emission tests was reported by Texaco Oil Corp. to have a hydrogen/carbon mass ratio of 0.148. Thus, the ratio of hydrogen to carbon atoms in the fuel is 1.76. Thus,

$$CH_{1.76} + 1.44\ O_2 + 5.46\ N_2 \rightarrow CO_2 + 0.88\ H_2O + 5.46\ N_2$$

Thus, 13.76 grams of fuel combine with 199.1 grams of air, or the stoichiometric air-fuel ratio is

$$\frac{199.1}{13.76} = 14.5$$

The error in the determination of stoichiometry using this method is to the extent that the composition of the fuel used in the test work was of the composition assumed in the calculation.

Stoichiometric Air-Fuel Ratio Determined by Engine Carbon Monoxide Variation

A common method of estimating stoichiometry is to observe the carbon monoxide variation with air-fuel ratio. A plot of carbon monoxide concentration versus air-fuel ratio at fixed throttle and engine speed will show an almost linearly decreasing CO level as the A/F increases from the rich side toward stoichiometry. This effect is due to the increasing

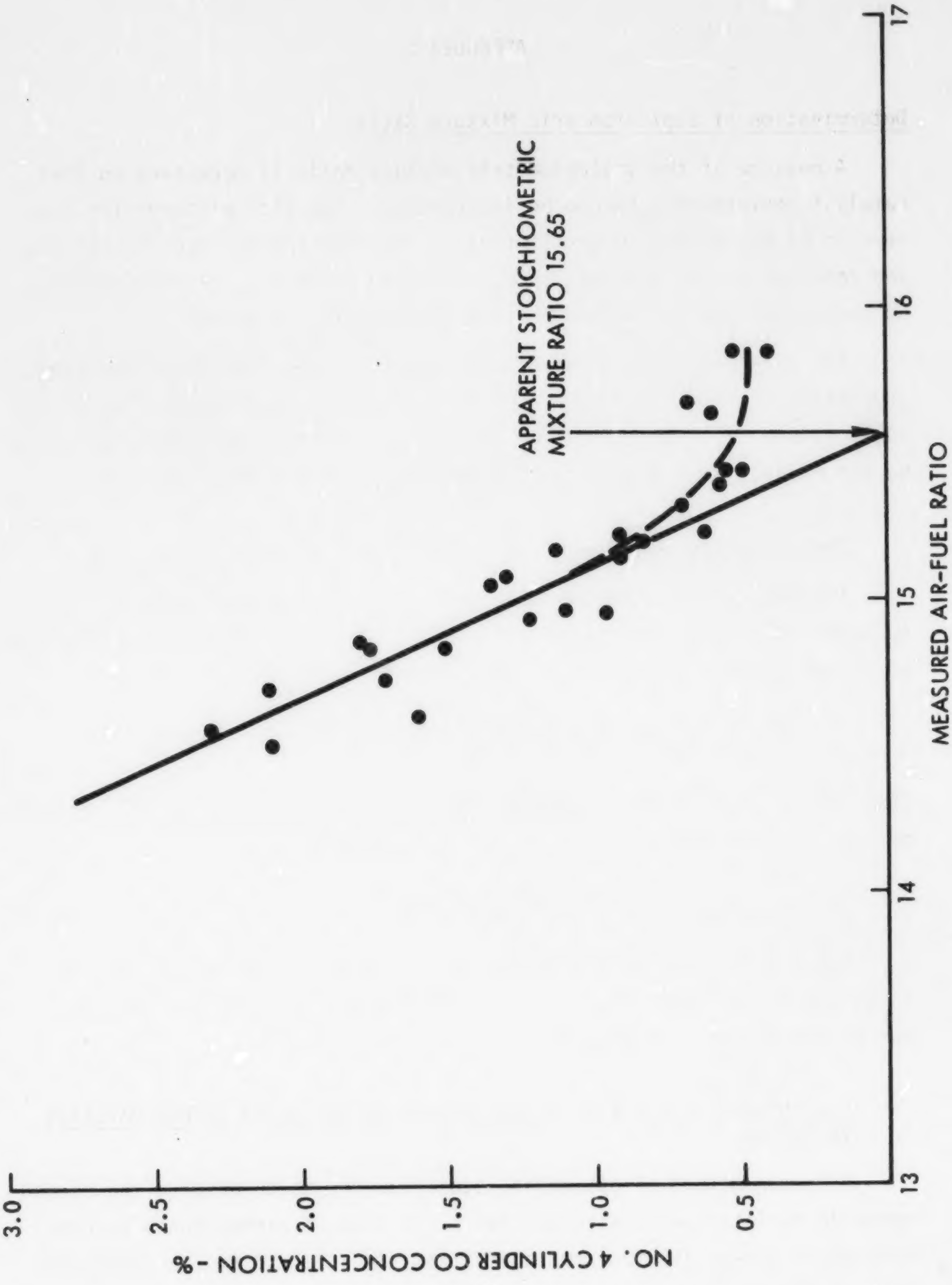

FIGURE J-1
DETERMINATION OF STOICHIOMETRY USING
EXHAUST CO FROM #4 CYLINDER OF VW 1600

degree of combustion completeness as more oxygen is available. Beyond stoichiometry, there is excess air for combustion; however, wall effects will insure that there will always be a small region in the cylinder where the reaction is quenched and combustion cannot go to completion. Thus, the CO concentration tends to remain flat for a small region lean of stoichiometry. A single cylinder's profile will exhibit a fairly sharp break in the CO curve; a multi-cylinder engine will have a less distinct break due to air-fuel variation among the cylinders.

Figure J-1 shows CO signature from the #4 cylinder of the VW engine as a function of indicated air-fuel ratio. The data shows an equivalence ratio of 1.0 at an indicated air-fuel ratio of 15.65.

It is interesting to note that a similar plot for the Vega exhaust does not indicate the narrow data spread and estimates of the stoichiometric air-fuel ratio using this technique have a much higher degree of uncertainty.

Stoichiometric Air-Fuel Ratio Determined by Oxidant-Reductant Balance

Another way of defining the stoichiometric air-fuel ratio is by finding the mixture ratio which results in equal exhaust oxidants and reductants. The oxidants in the exhaust are O_2 and NO; reductants are HC, H_2 and CO. (There may be amounts of C-N or N-H compounds in the exhaust but they are so small as to be within the accuracy of measuring the primary species.)

The error in determining stoichiometry by this technique depends on the errors in the individual concentration measurements. However, this method has the advantage that for multi-cylinder engines, the exhaust stream make-up does not depend on the mixture ratio in each cylinder but the gross mixture ratio at the carburetor. When the catalytic converter works on the total stream as in the full scale emission tests with the Vega and the full scale TRW-Harshaw converter only the overall mixture ratio is important for catalyst operation.

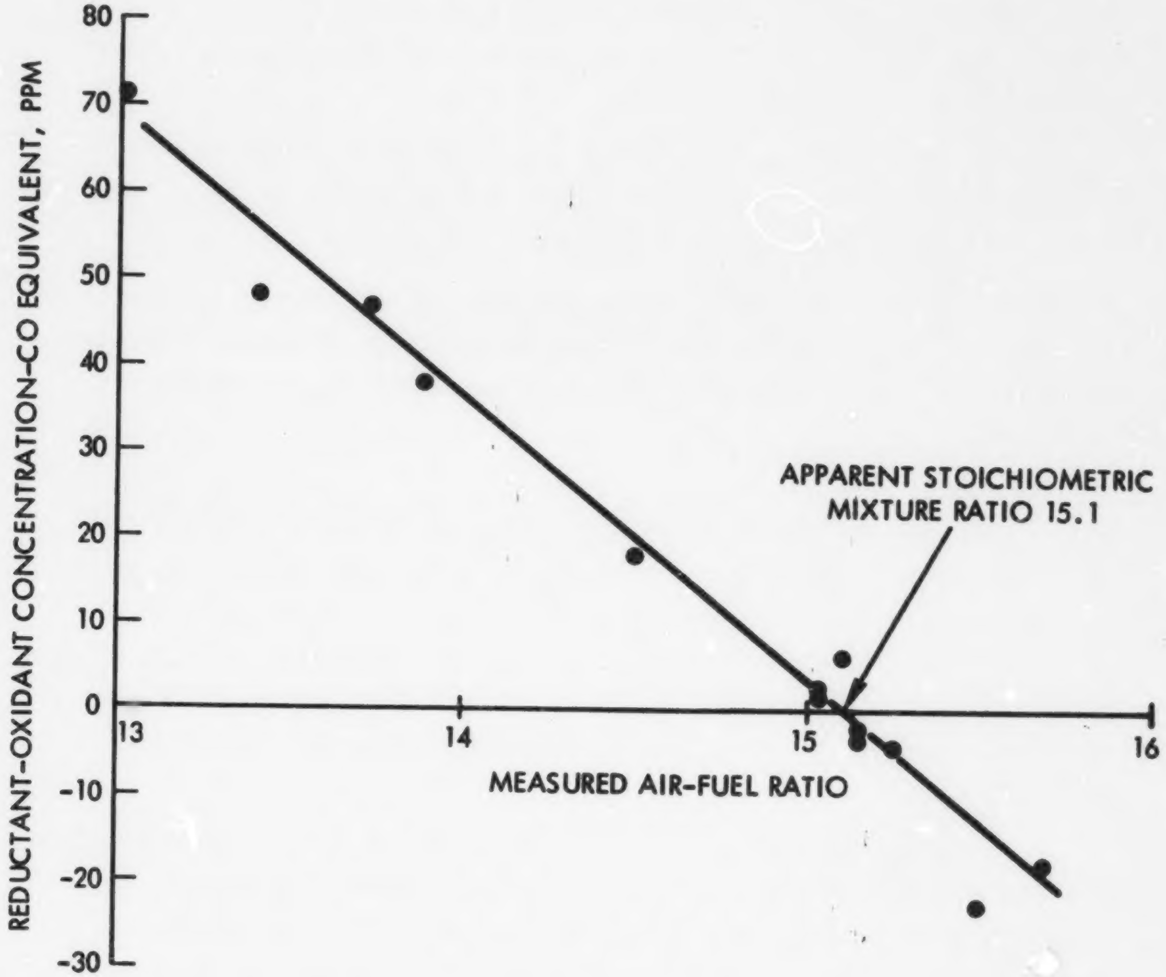

FIGURE J-2
DETERMINATION OF STOICHIOMETRY FROM
REDUCTANT-OXIDANT BALANCE IN VEGA EXHAUST

Figure J-2 presents the difference in reductants and oxidants from the Vega engine as a function of the indicated air-fuel ratio. The difference is expressed in CO equivalents; that is, the reducing potential of a single CO molecule is 1 ppm. The reductant-oxidant difference equals zero at stoichiometry and in the Vega tests stoichiometry appears at a measured A/F equal to 15.1.

From the previous discussions it is apparent that the stoichiometric mixture ratio is difficult to establish. The engine CO method gave over one point higher A/F ratio than the fuel composition reading, a difference of about 7%. On the other hand, the two experimental methods differ by only about 3.7%, which suggests that there may be a systematic error in measuring the A/F ratio and accounts for the grouping of the experimental points away from the calculated value.

The Flowtron fuel flowmeter was calibrated in-situ on the dynamometer using a catch and weigh technique. Periodic checks of the calibration suggested that the maximum error in fuel measurements would not exceed 3% in the fuel flow range of these experiments.

The accuracy of the Meriam Laminar Flow Meter is stated as ±0.5% full scale. For the devices used in this test, that corresponds to about 0.5 cfm or about ±2% error in the air-flow ranges used in the tests.

Another source of error in using the Meriam Instrument is the correction of the volume flow rates to standard conditions. In the case of the single cylinder tests with the VW engine, the air temperature was read on a mercury-in-glass thermometer mounted in free air about five feet from the engine air inlet. There is no way of knowing exactly how much the temperature of the air in the inlet flow varied from cell air. However, a 10°F difference could have been possible with the engine inlet air hotter than the cell air. This temperature difference would have introduced a 3% error in the air flow; the actual flow rate would be less than the measured. This of course would tend to overestimate the air-fuel ratio by 3%.

The above considerations suggest the following:

- The differences between the calculated stoichiometric A/F and the two experimental techniques may be attributed to systematic errors in measuring the air and fuel flow rates.
- The differences between the two experimental techniques can be partially accounted for by improper temperature corrections of the air flow rate in the VW test work. Additional differences are possible due to curve fitting errors and errors in measuring the oxidant/reductant specie concentrations.

The following procedure was thus adopted for reporting all the characterization data. For the single cylinder catalyst tests all data is referenced to a stoichiometric mixture ratio of 15.65. For all full scale catalyst work using the Vega engine all data is referenced to a stoichiometric mixture ratio of 15.1.

APPENDIX K

Engine Modifications, Instrumentation and Test Fuel

The 1971 Chevrolet Vega engine used in the full scale hybrid system emission tests was purchased from a salvage yard. The engine had accumulated approximately 3000 miles of vehicle operation. The Vega is an inline, overhead cam four cylinder engine with a displacement of 140 cubic inches. The engine used was the higher-powered version of the engine which uses a two-barrel downdraft carburetor and is advertised as having a peak power output of 110 hp at 4800 rpm.

The alternator of the engine was removed for these tests, however the water pump, starter motor, fan and ignition system were left untouched. A radiator from a 1963 Pontiac Tempest was used for cooling.

Initially, it was planned to use the two-barrel carburetor in conjunction with a combination of fuel bowl pressurization and external needle valving in the main fuel circuit for air-fuel ratio control. However, severe problems were encountered in this approach. The engine proved difficult to start lean as it was hard to establish the proper needle valve settings from run to run. Secondly, at mixtures leaner than stoichiometry the engine had a tendency to surge under load. Finally, there were problems of fuel flow resolution and repeatability. For these reasons, the carburetor modification approach was abandoned.

In its place, we chose a form of intake manifold fuel injection. The manifold pressure transducer, four fuel injectors and fuel pump from the VW 1600 engine were combined with specially built injector control electronics to provide a well regulated, easily adjusted fuel control system. A photograph of the installation on the Vega is shown in Figure K-1.

A plenum box was constructed to serve as; a mounting plate on the intake manifold, a mounting plate for the injectors, a mounting plate for the butterfly valve body of the Vega carburetor, and a return port for the hydrocarbon accumulator desorption line. Engine air was drawn in through a Meriam laminar flow element flowmeter and across the butterfly valve which was controlled by a cable from the control/instrumentation room area. The air then was turned through two 90^0 bends into the intake manifold.

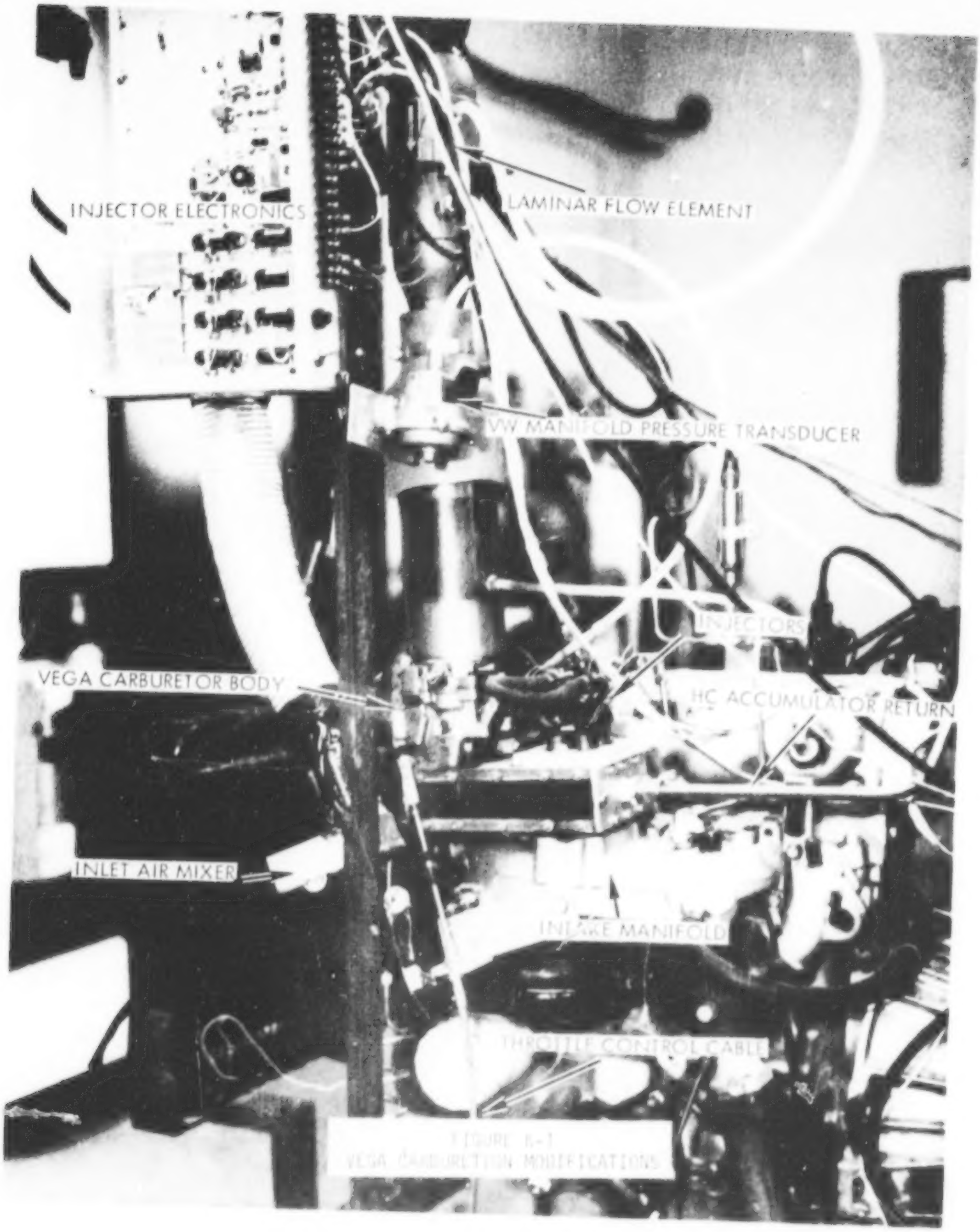
INJECTOR ELECTRONICS
LAMINAR FLOW ELEMENT
VW MANIFOLD PRESSURE TRANSDUCER
INJECTORS
VEGA CARBURETOR BODY
HC ACCUMULATOR RETURN
INLET AIR MIXER
INTAKE MANIFOLD
THROTTLE CONTROL CABLE

FIGURE 6-1
VEGA CARBURETION MODIFICATIONS

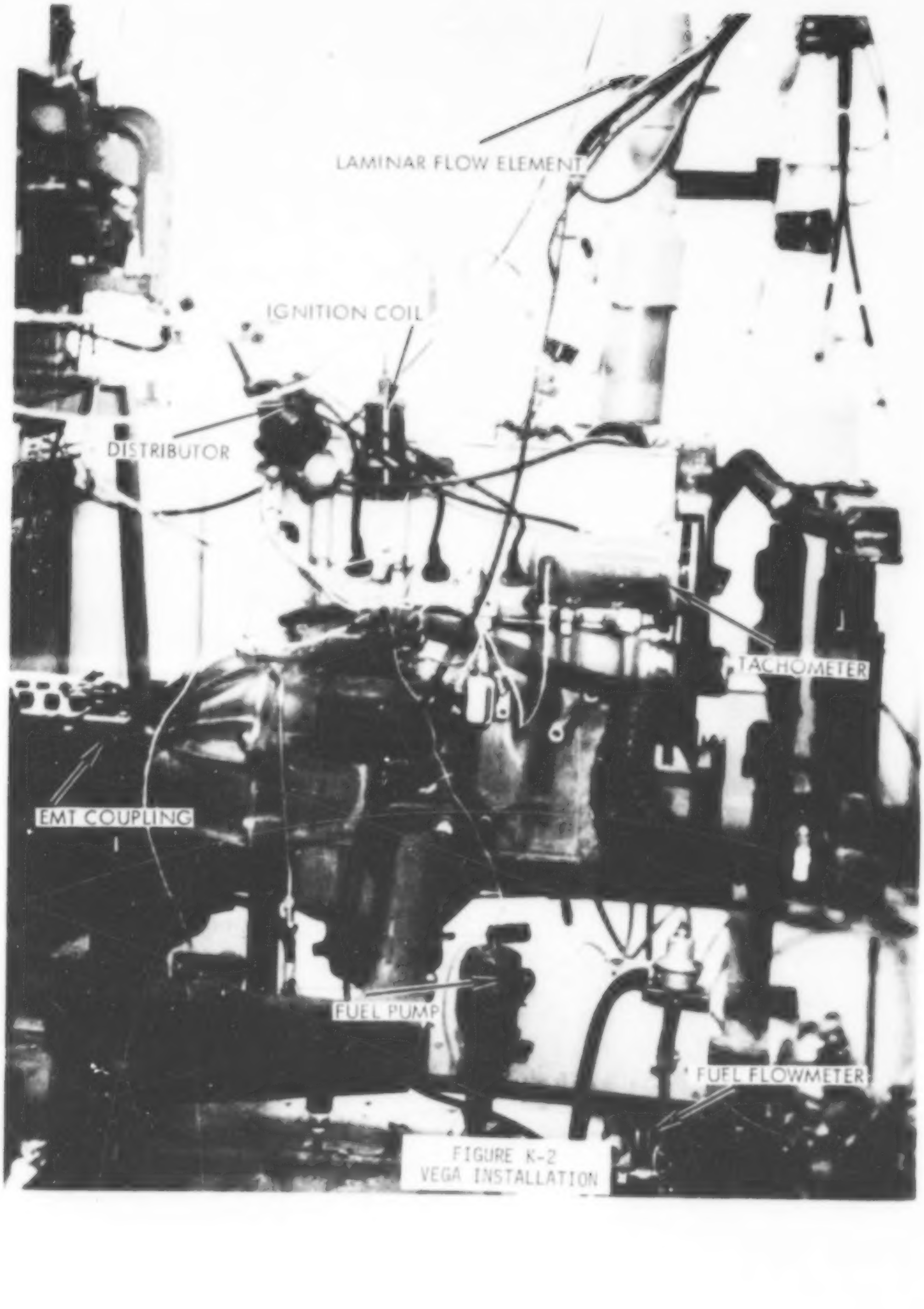
LAMINAR FLOW ELEMENT
IGNITION COIL
DISTRIBUTOR
TACHOMETER
EMT COUPLING
FUEL PUMP
FUEL FLOWMETER

FIGURE K-2
VEGA INSTALLATION

The four injectors from the VW were mounted in a gang so that their spray was directed down into the opening in the intake manifold casting. The injectors were fired as a group. Basic engine speed and injection pulse initiation were supplied to the injector control electronics by a set of extra point contacts mounted within the distributor. These contacts were activated by the distributor cam and thus an injection pulse was initiated for each spark plug firing event. The basic duration of each pulse was controlled by the decay of an L-R circuit. The L portion of the circuit was provided by the VW manifold pressure transducer which uses a diaphram-driven variable reluctance coil. The variable R portion of the circuit was a Helipot resistor controlled from the control room area. The Helipot had sufficient resistance capacity to change the L/R time constant of the circuit so that air-fuel ratio control over a wide range was possible with a high degree of resolution.

The position of the four injectors over the intake manifold opening was found to be very important for a uniform emission profile from each cylinder. Exhaust sample taps were installed in each leg of the exhaust manifold and individual cylinder emission signatures were compared as the injector group was moved about the top of the plenum box. After considerable trial and error, a balance was found which gave rise to no more than a 10% variation in the NO-CO levels among the four cylinders.

Several other minor modifications were made to the engine some of which can be seen in Figures K-1 and K-2. The bimetallic element-controlled damper valve in the air cleaner and the heat riser shroud over the exhaust manifold were modified slightly. With the engine cold, the valve was manually set so that engine air was drawn over the exhaust manifold, through the valve and LFE into the plenum box. When the air temperature in the LFE reached 100°F, the valve was manually operated so that air was drawn in from the test cell, bypassing the exhaust manifold.

The timing belt cover was cut away so that a drive disc on a DC tachometer could be pressed against the outside of the belt. The tachometer was driven by friction; its output was used as a measure of engine speed and was the primary feedback signal to the EMT system for engine speed control.

The starter motor was powered from a 24 volt battery package. The increased voltage was used to insure a high cranking speed and elimination of poor starting conditions. The coil was fed from a 12 volt tap on the 24 volt supply.

The clutch assembly and drive shaft from the driven clutch plate into the gear box was modified. The shifting level was operated by a small pneumatic cylinder allowing the engine to be remotely coupled or uncoupled from the EMT system. The drive shaft was machined so that it could be coupled to a Baldwin-Lima-Hamilton Torque Transducer. The other end of the torque transducer mated with the sun gear of the planetary gear portion of the EMT. The torque transducer was used in the initial phases of the Vega development to calibrate the engine output power at various manifold pressures and air-fuel ratios. In later experiments, the torque transducer was eliminated.

Gasoline Used in Tests

In all the emission tests using the VW 1600 or Vega engines, a single gasoline was used. Texaco "lead free" gasoline was purchased from a local service station in ten gallon batches, thus the fuel composition reflects what was available at that service station over the duration of the program.

The VW engine had been run on lead-free gasoline for over six months prior to the start of the program in an attempt to burn out any lead deposits which might have accumulated prior to this work. The gasoline used in the Vega prior to its acquisition is unknown; however it was felt that there was substantial running with unleaded gasoline on the dynamometer prior to catalyst tests to have eliminated any small lead buildup.

The research laboratories of Texaco reported that their lead free gasoline marketed in the Los Angeles area had the following properties:

- 91 research octane number
- hydrogen/carbon mass ratio - 0.148
- distillation data--
    - 98°F initial boiling fraction
    - 10% evaporation at 131°F
    - 50% evaporation at 233°F
    - 90% evaporation at 326°F
    - 407°F final boiling fraction

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